Interannual atmospheric variability forced by the deep equatorial Atlantic Ocean

Peter Brandt[1], Andreas Funk[1],
Verena Hormann[1, 2], Marcus Dengler[1],
Richard J. Greatbatch[1], John M. Toole[3]

[1]IFM-GEOMAR, Kiel, Germany
[2]CIMAS and NOAA/AOML, Miami, USA
[3]WHOI, Woods Hole, USA

Outline

- Introduction
  - Atlantic Cold Tongue and Zonal Mode
- 4.5-year Climate Cycle
- Deep Ocean Dynamics
  - Argo Float Data
  - Introduction Equatorial Deep Jets
  - Moored Observations
  - Shipboard Observations
  - Observation versus Model
- Summary and Discussion
  - Global Ocean Perspective
  - SST Data Sets

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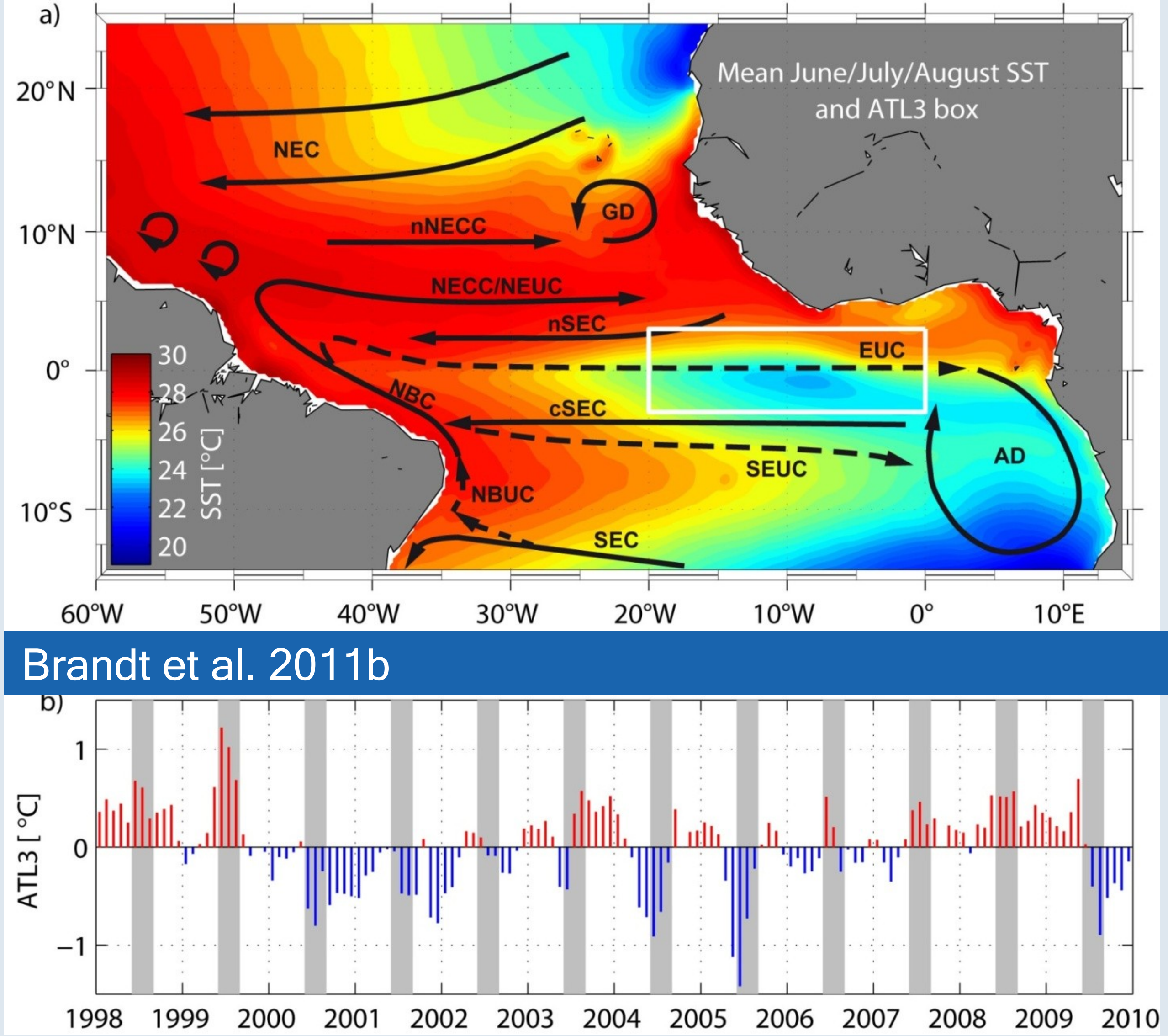
Equatorial Atlantic Cold Tongue

- Cold tongue develops during boreal summer
- Strong interannual variability of ATL3 SST index (3°S-3°N, 20°W-0°)



Brandt et al. 2011b

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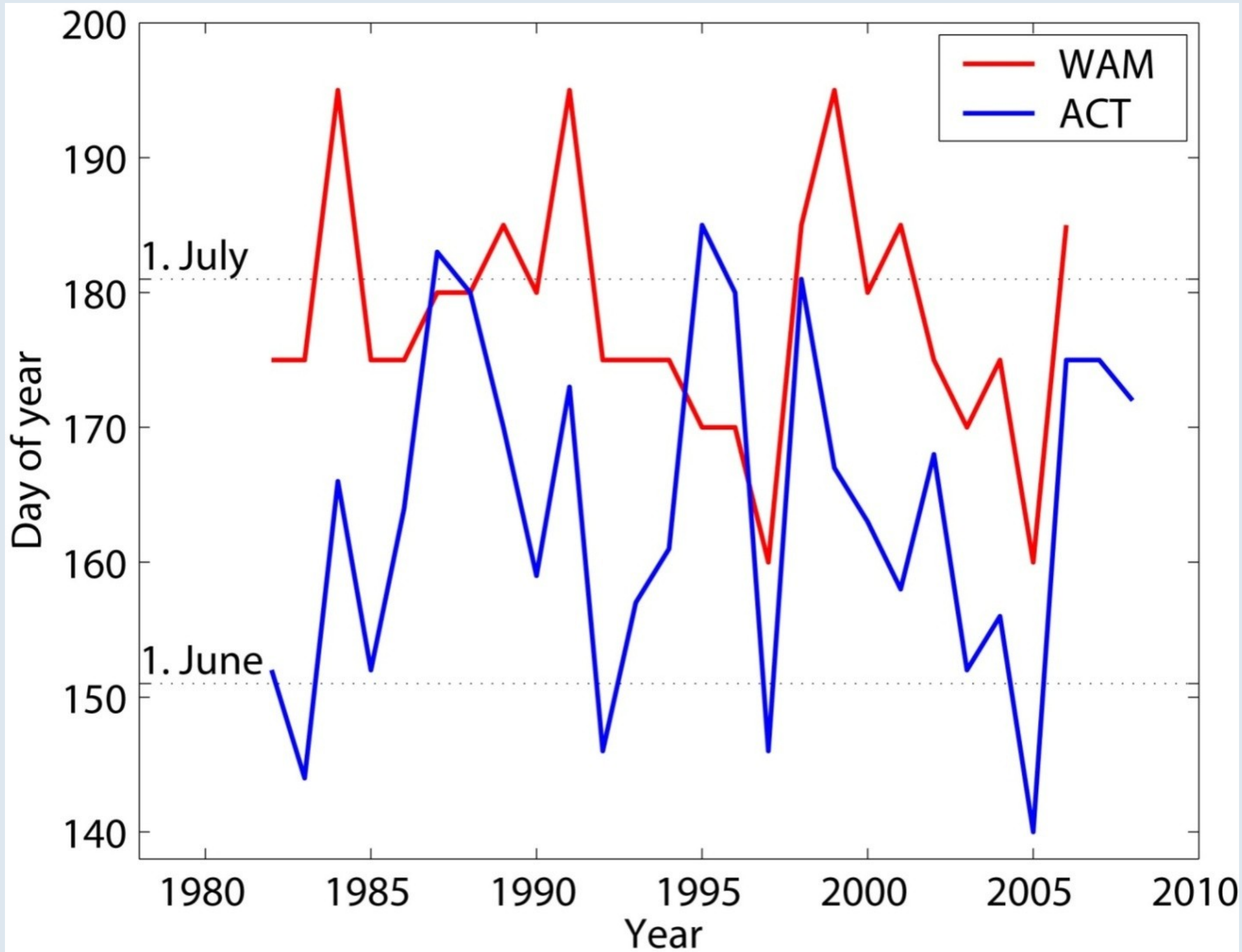
Onset of Atlantic Cold Tongue and West African Monsoon

- WAM onset follows the ACT onset by some weeks
- Significant correlation of ACT and WAM onsets



WAM onset – northward migration of rainfall (10°W-10°E.) (*Fontaine and Louvet, 2006*)
ACT onset – surface area (with T<25°C) threshold

Brandt et al. 2011b, Caniaux et al. 2011

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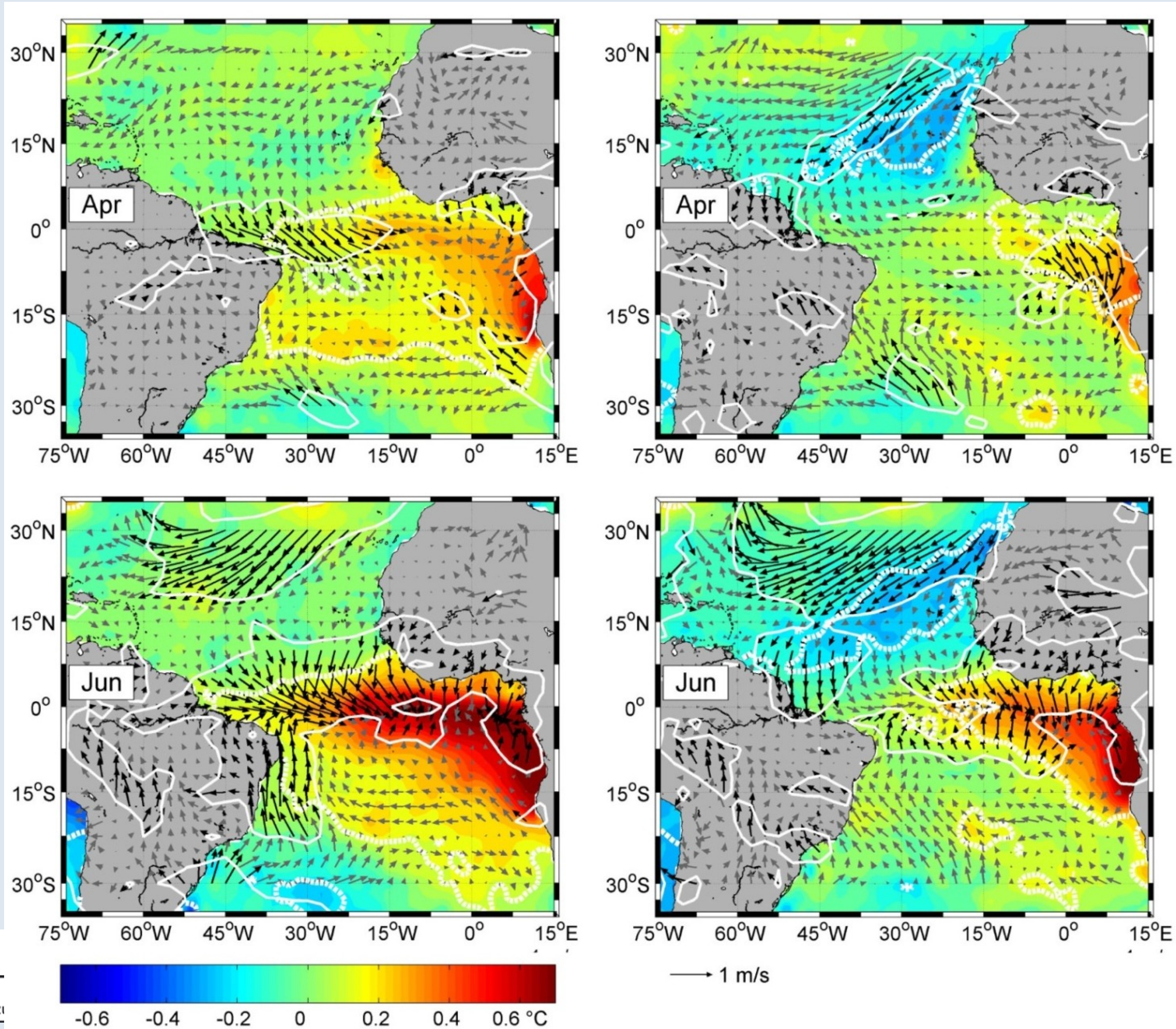
Regression of SST and Wind onto

ACT Onset

Cold tongue SST; Wind forcing in the western equatorial Atlantic (zonal mode)

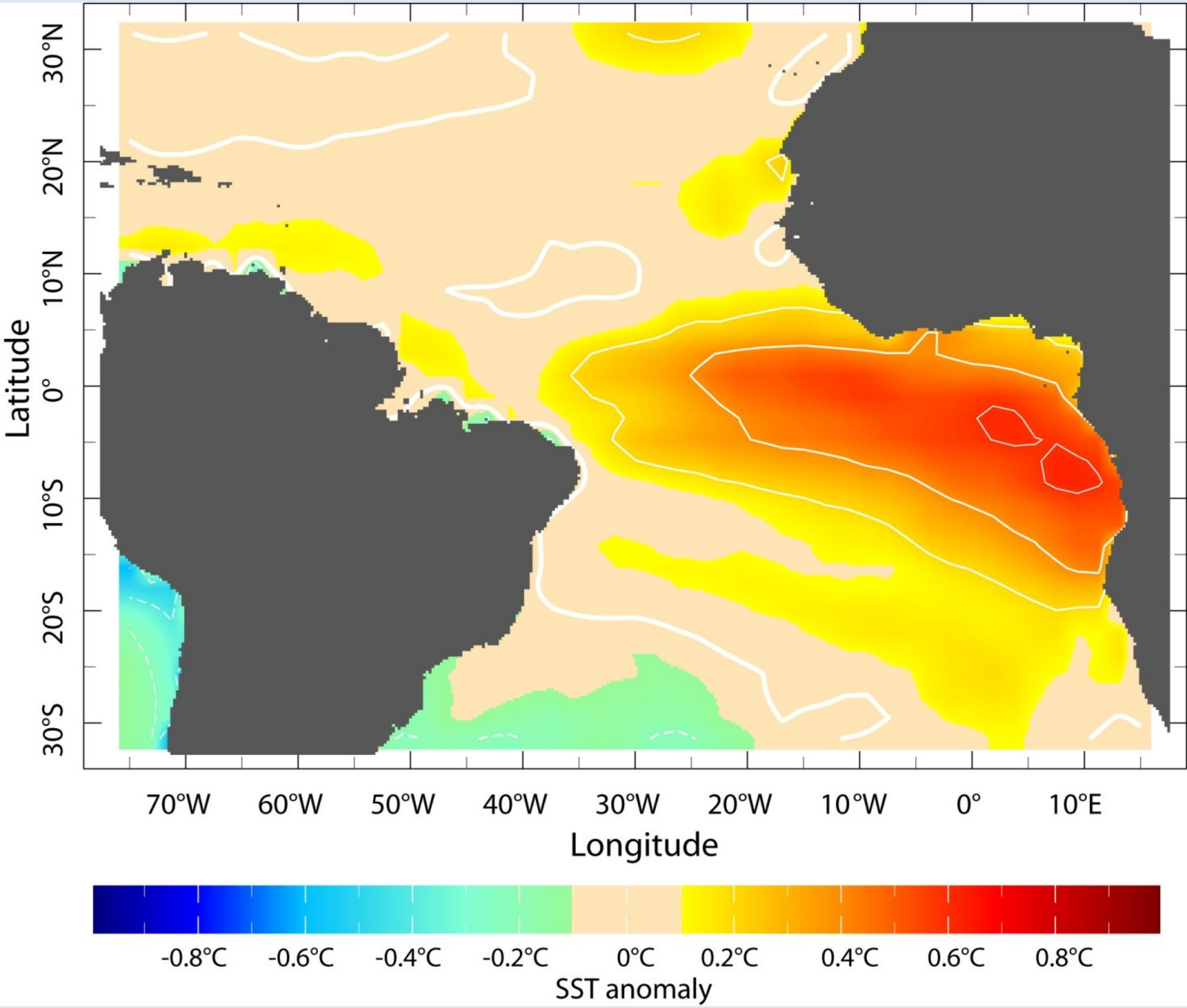


WAM Onset

Significant correlation with cold tongue SST (zonal mode) and SST in the tropical NE Atlantic (meridional mode)

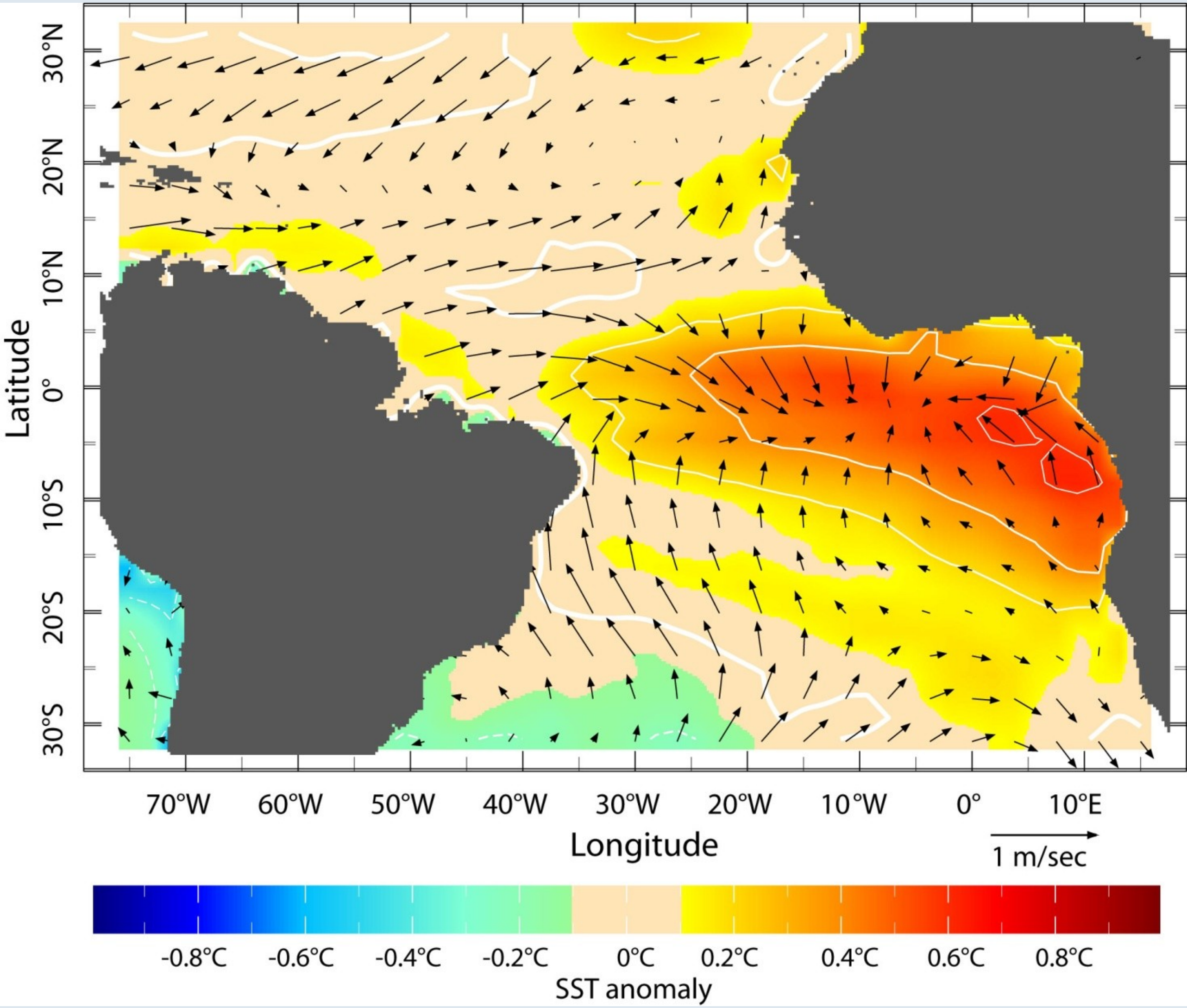
Zonal Mode (June-August)

- June-August SST anomaly (colors, in °C & white contours, every 0.2°) determined by regression on the time series of the first June-August rainfall EOF (33%)



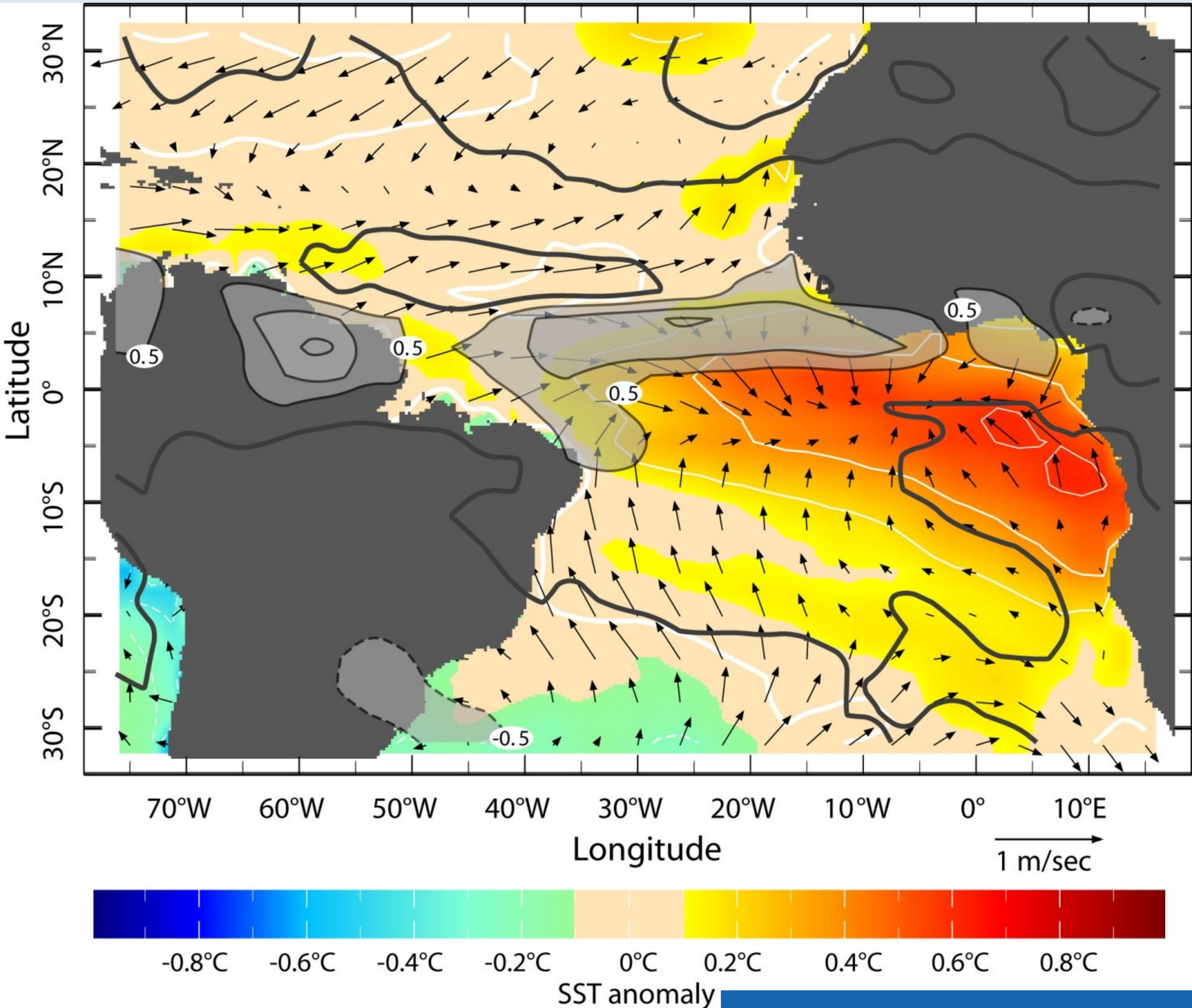
Zonal Mode (June-August)

- June-August SST anomaly (colors, in °C & white contours, every 0.2°) and surface wind anomaly (vector, in m/sec) determined by regression on the time series of the first June-August rainfall EOF (33%)



Zonal Mode (June-August)

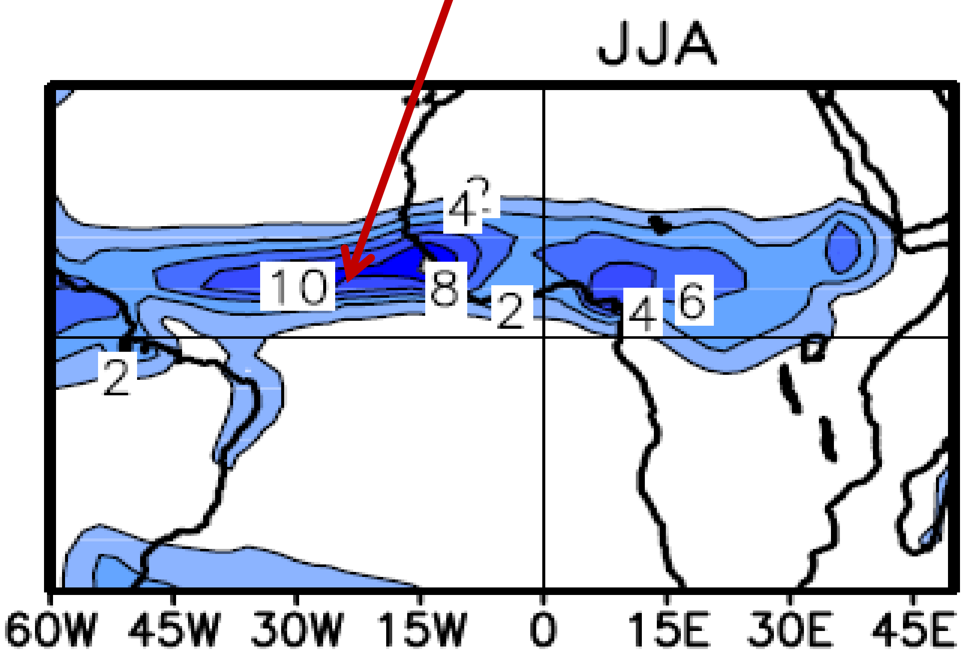
- First EOF (33%) of the June-August rainfall from GPCP 1979-2001 (contours in mm/day). June-August SST anomaly (colors, in °C & white contours, every 0.2°) and surface wind anomaly (vector, in m/sec) are determined by regression on the time series of the rainfall EOF



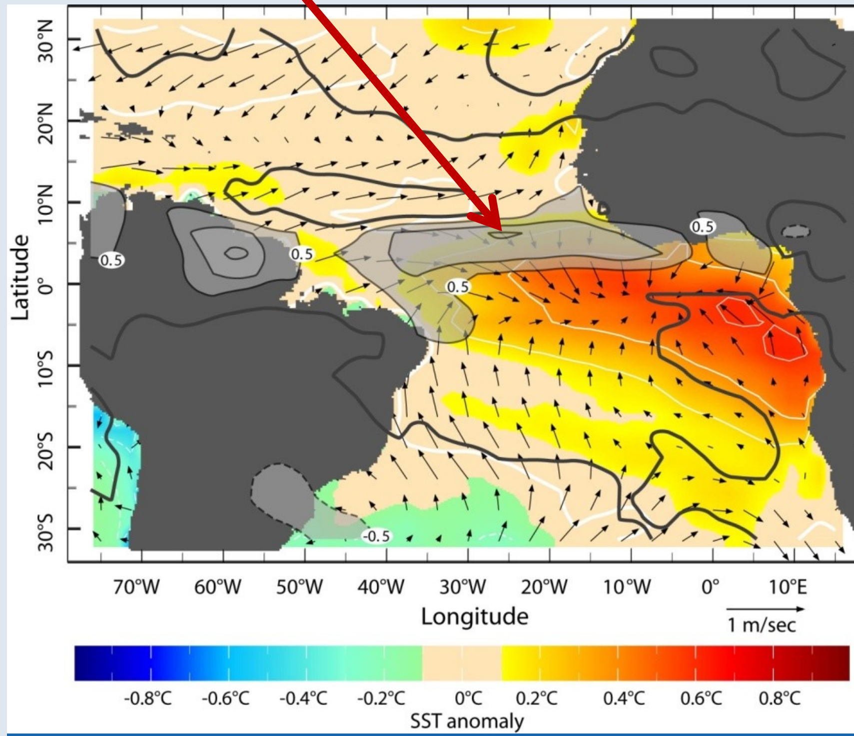
Kushnir et al. 2002

Zonal Mode (June-August)

Average precipitation [mm/day] during boreal summer



First EOF of interannual variability of boreal summer precipitation [mm/day]



Chang et al. 2006, Kushnir et al. 2006

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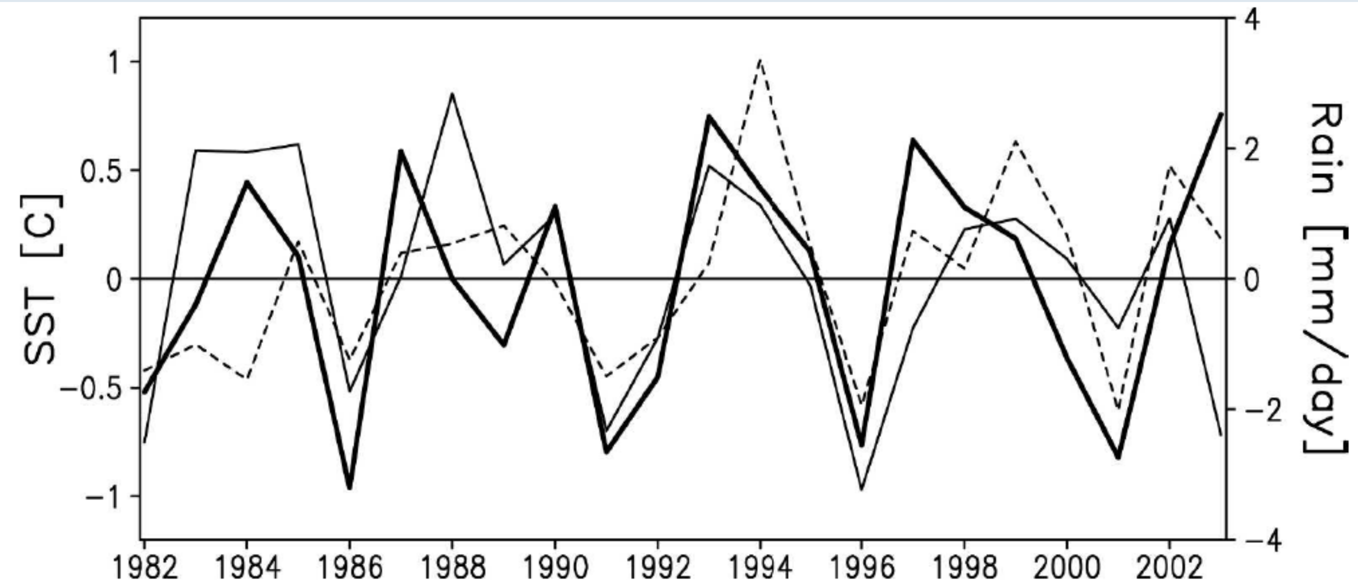
Bjerkness Feedback Active during Cold Seasons

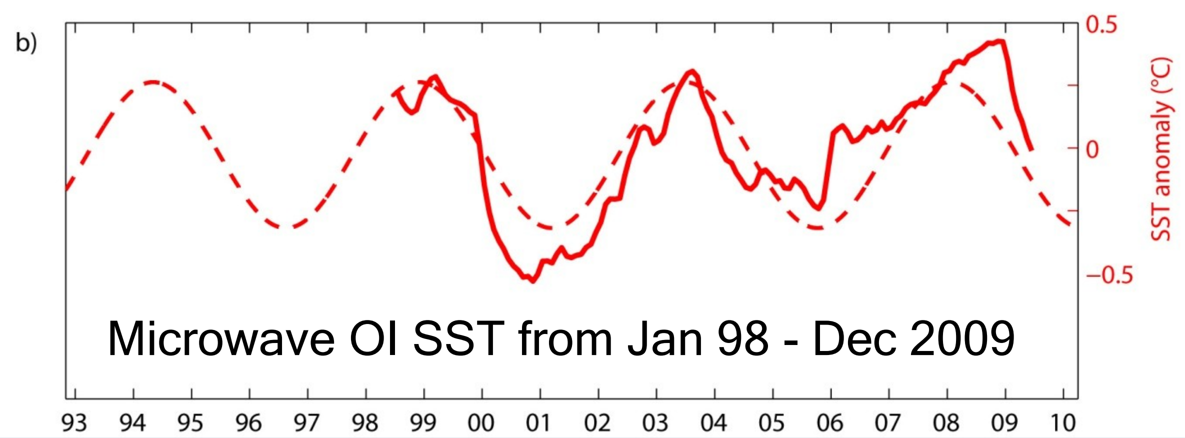
- Keenlyside and Latif (2007)
  - Bjerkness feedback in the Atlantic weaker than in the Pacific
  - Strong during boreal spring/summer associated with zonal mode
- Okumura and Xie (2006)
  - Secondary cooling during Nov/Dec $\Rightarrow$ **Nino II**
  - Warm and cold events occur every 4-6 years (thick solid)
  - Associated with Nov/Dec rainfall anomaly in coastal Congo-Angola (dashed)



Okumura and Xie 2006

ATL3 Sea Surface Temperature

- ATL3 SST anomaly (running annual mean)
- Maximum explained variance found at 1670d or 4.5 years (harmonic fit)



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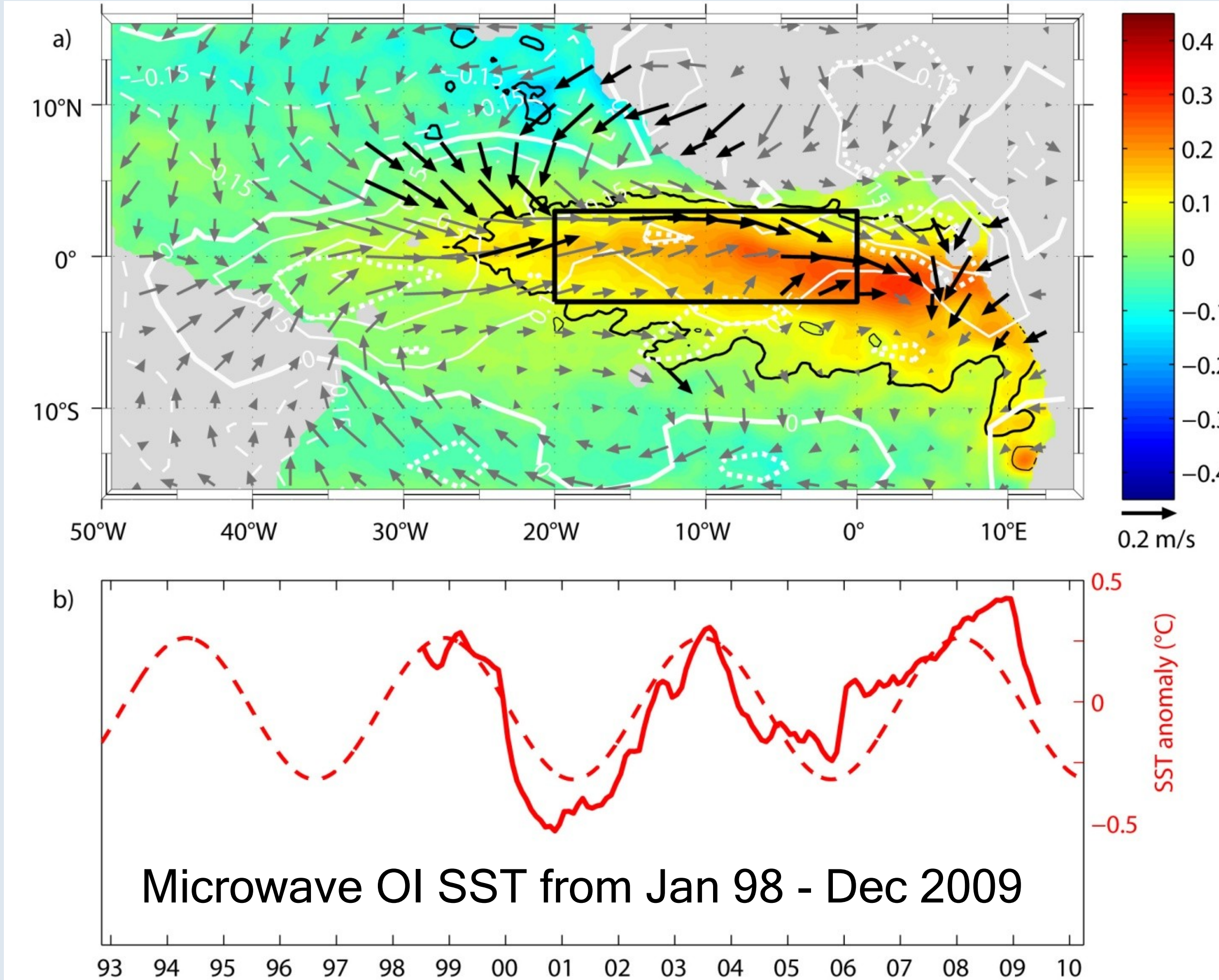
4.5-year Climate Cycle

- Regression of SST (color), wind (arrows), and rainfall (contours) onto 4.5-year harmonic fit



Brandt et al. 2011a

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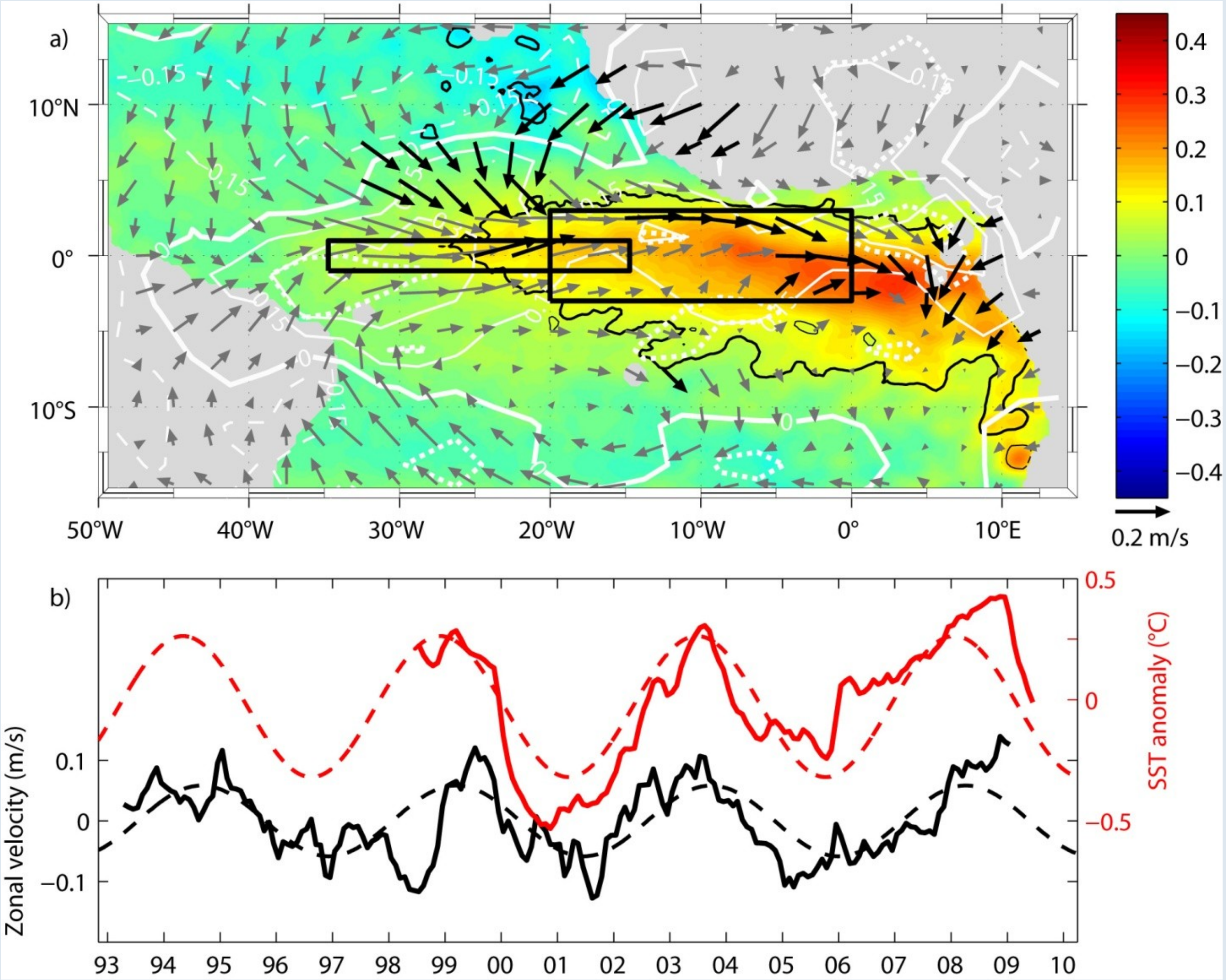
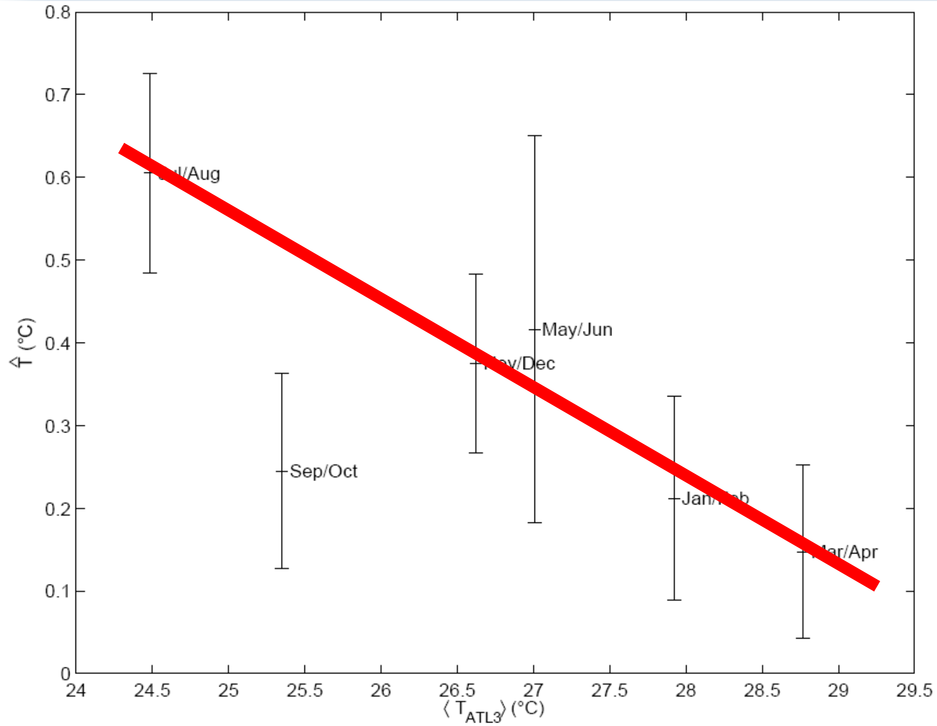
Surface Geostrophic Velocity

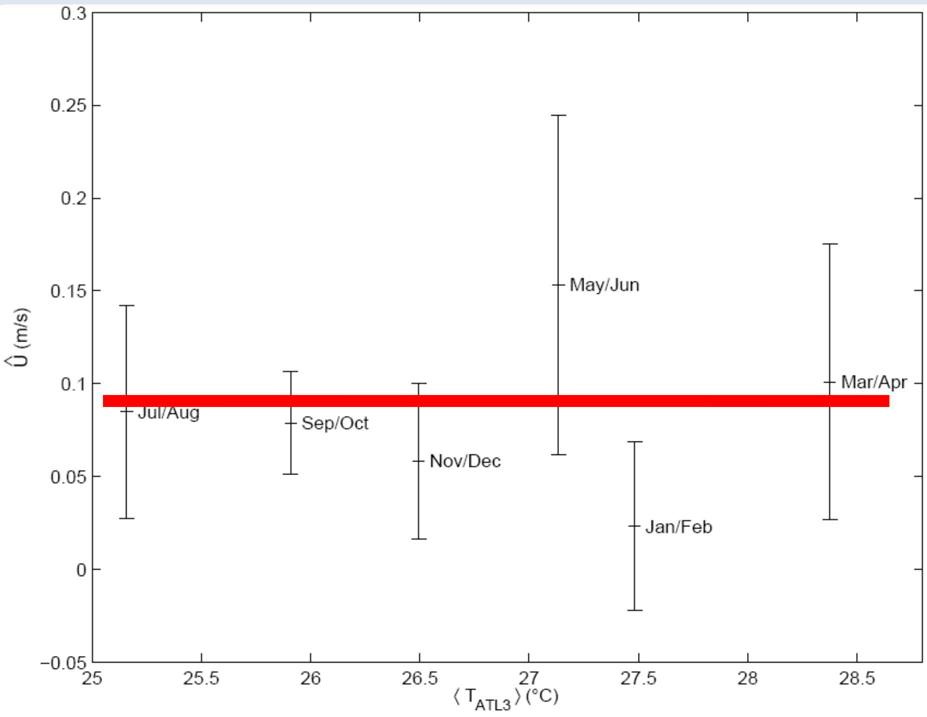
- Geostrophic equatorial zonal surface velocity (from sea level anomalies 15°W-35°W) show a similar 4.5-year cycle



Seasonal Dependence

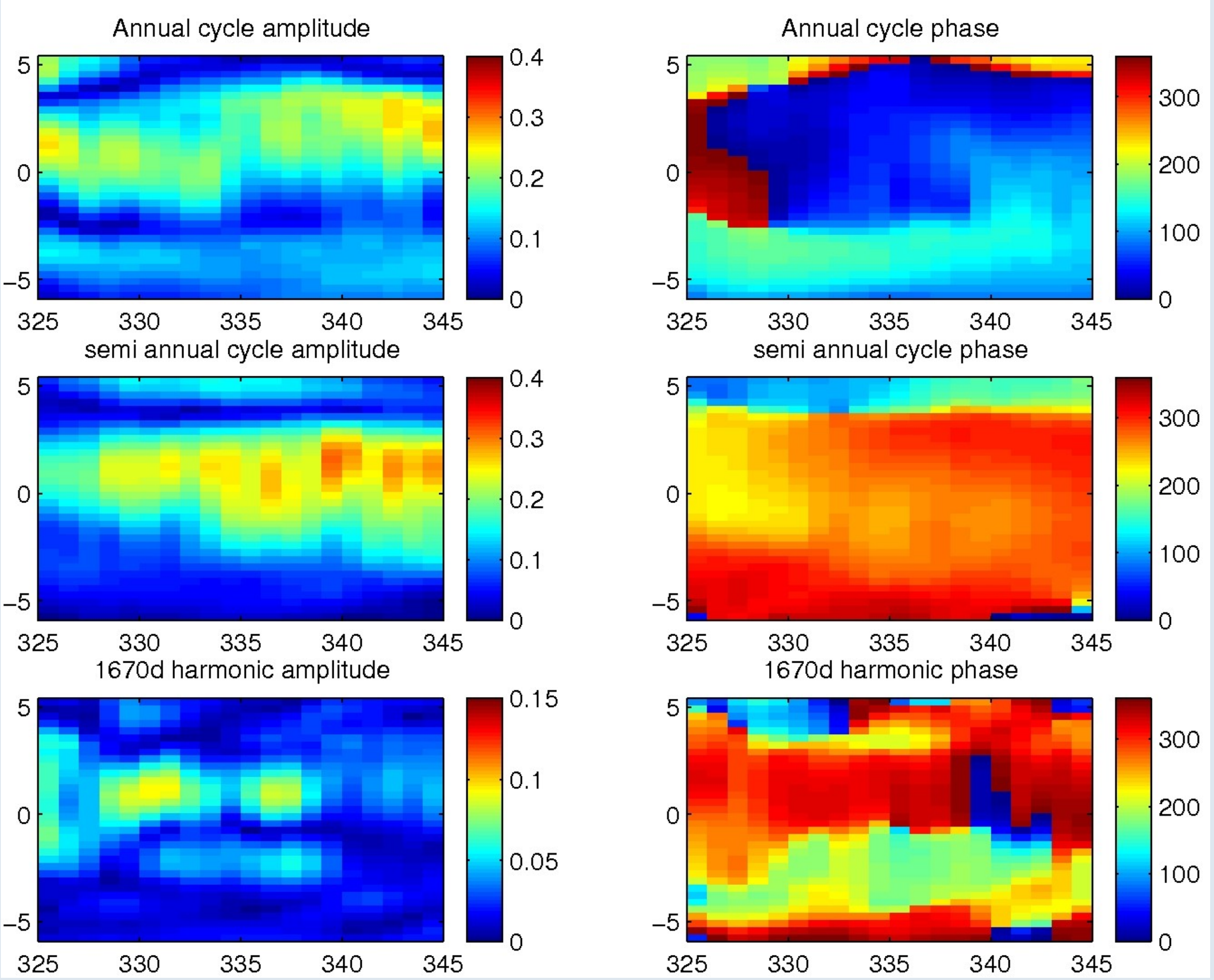
- Amplitude of the 4.5-year cycle of SST has maximum values during boreal summer and Nov/Dec (cold seasons with active Bjerknes feedback)
- 4.5-year cycle of surface velocity seasonally independent





Meridional Structure of Zonal Geostrophic Surface Velocity

- 4.5-year cycle is more confined to the equator than the annual and semiannual cycle.



Different harmonic cycles of zonal velocity.

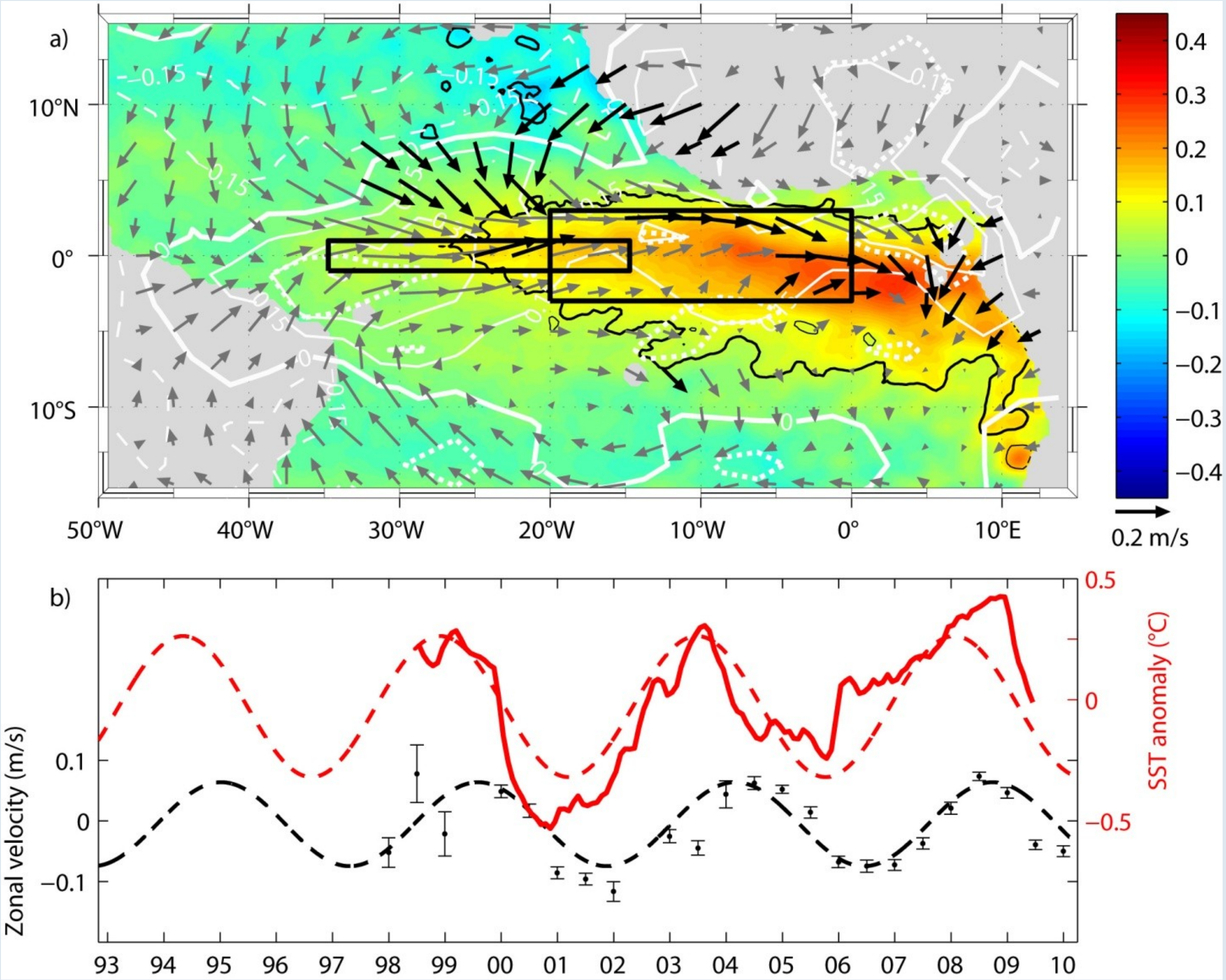
What drives the 4.5-year cycle at the sea surface?

- Winds are more irregular; equatorial ocean response at long periods is a succession of equilibrium responses with the strength of the flow independent of the forcing period (Philander & Pacanowski 1981)
- Periods of zonal-mode-like oscillations estimated from observations, models and theory ranges from 19 months to 4 years (e.g. Zebiak 1993, Ruiz-Barradas et al. 2000, Ding et al. 2010)
- External forcing is needed (Wang & Chang 2008)

$\Rightarrow$ **Deep Equatorial Ocean Dynamics!**

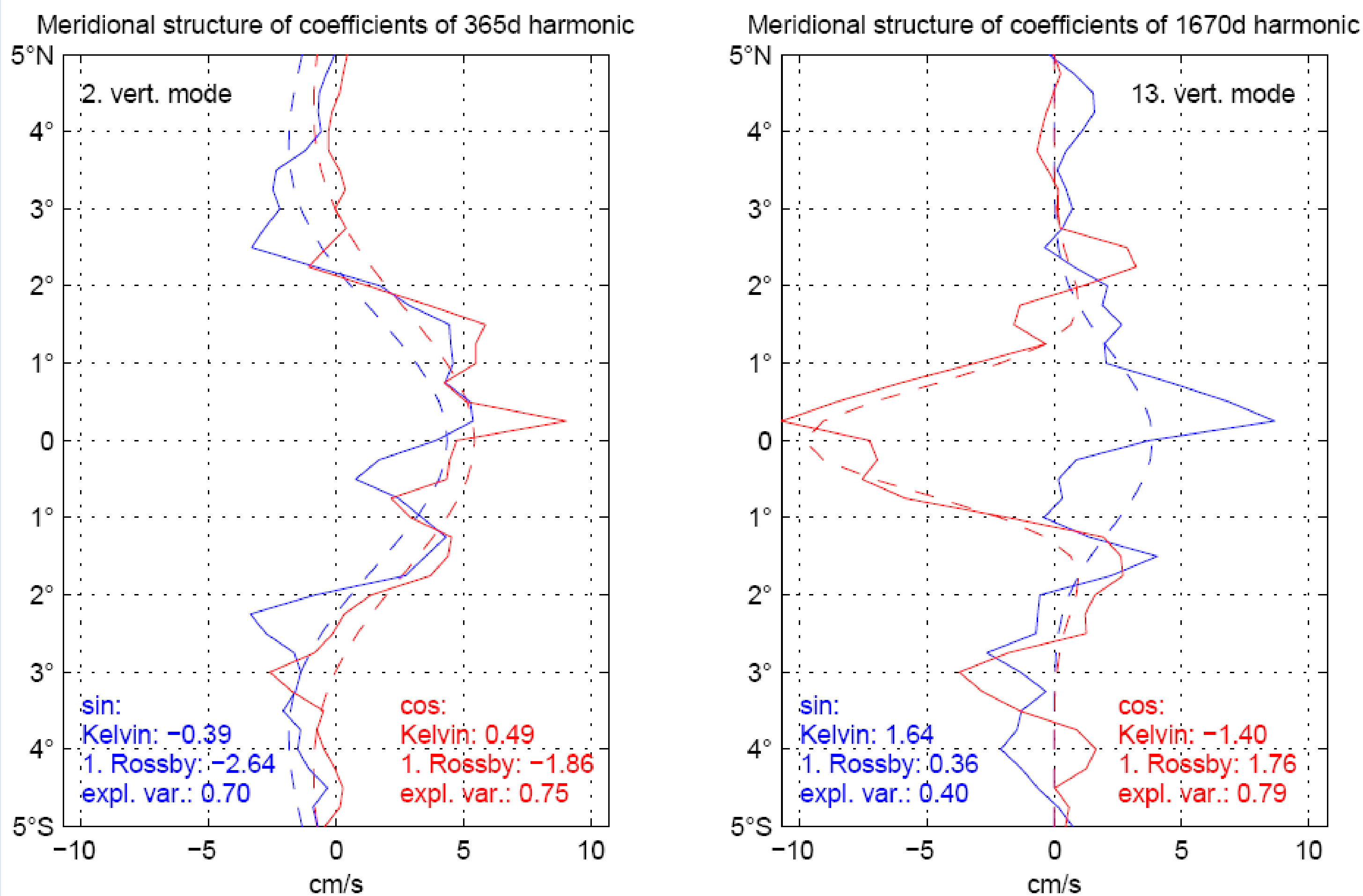
Deep Ocean Zonal Flow

- 1000m zonal velocity from Argo floats show the same 4.5-year cycle (annual means within 1°S-1°N, 15°W-35°W).



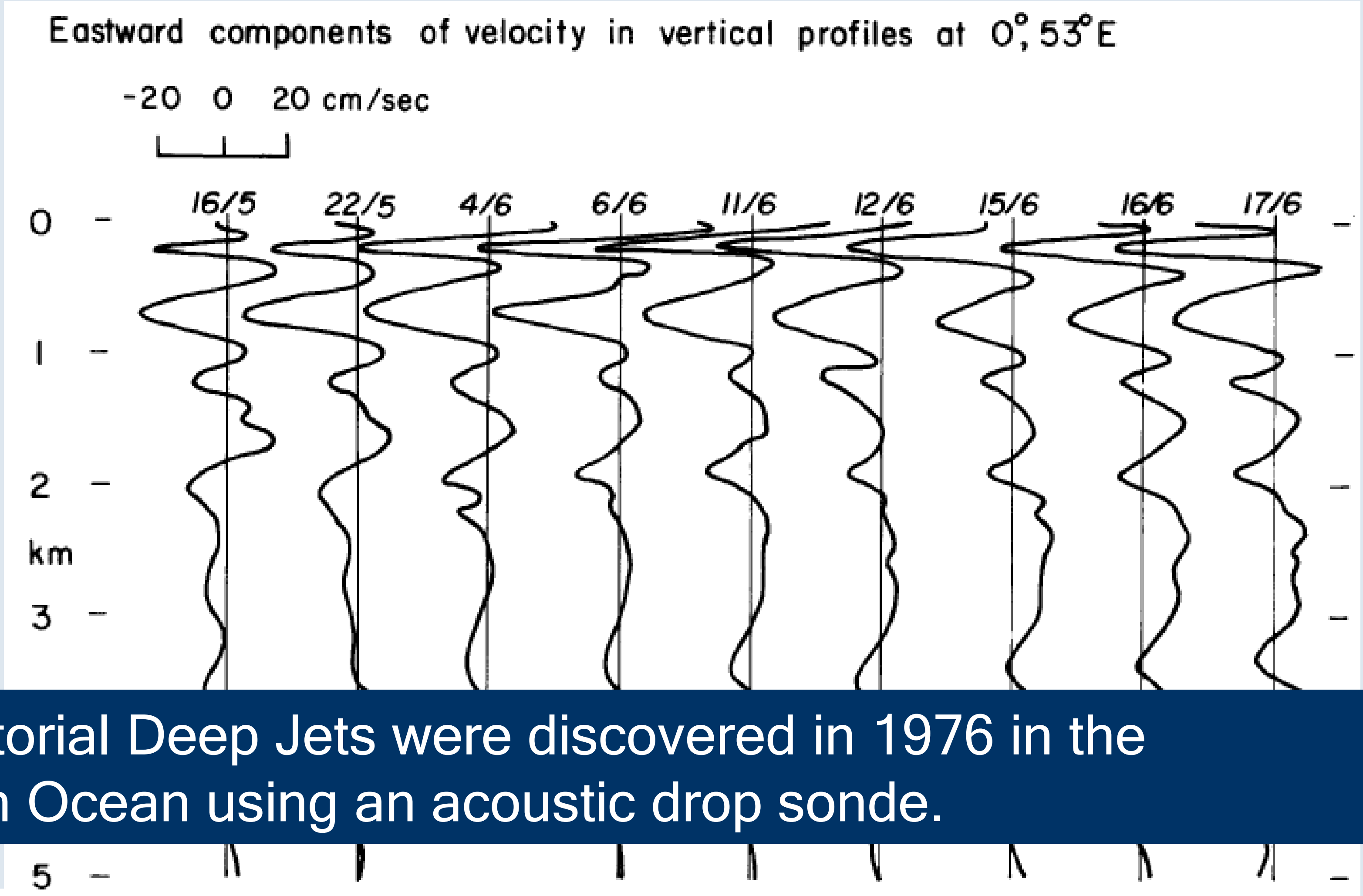
Meridional Structure of the Argo float velocities

While the annual cycle is best explained by a second boroclinic mode,
the 4.5-year cycle is associated with high-baroclinic mode waves - mixture of Kelvin and Rossby waves



By courtesy of Sven-Helge Didwischus

Equatorial Undercurrents



Equatorial Deep Jets were discovered in 1976 in the Indian Ocean using an acoustic drop sonde.

Luyten & Swallow 1976

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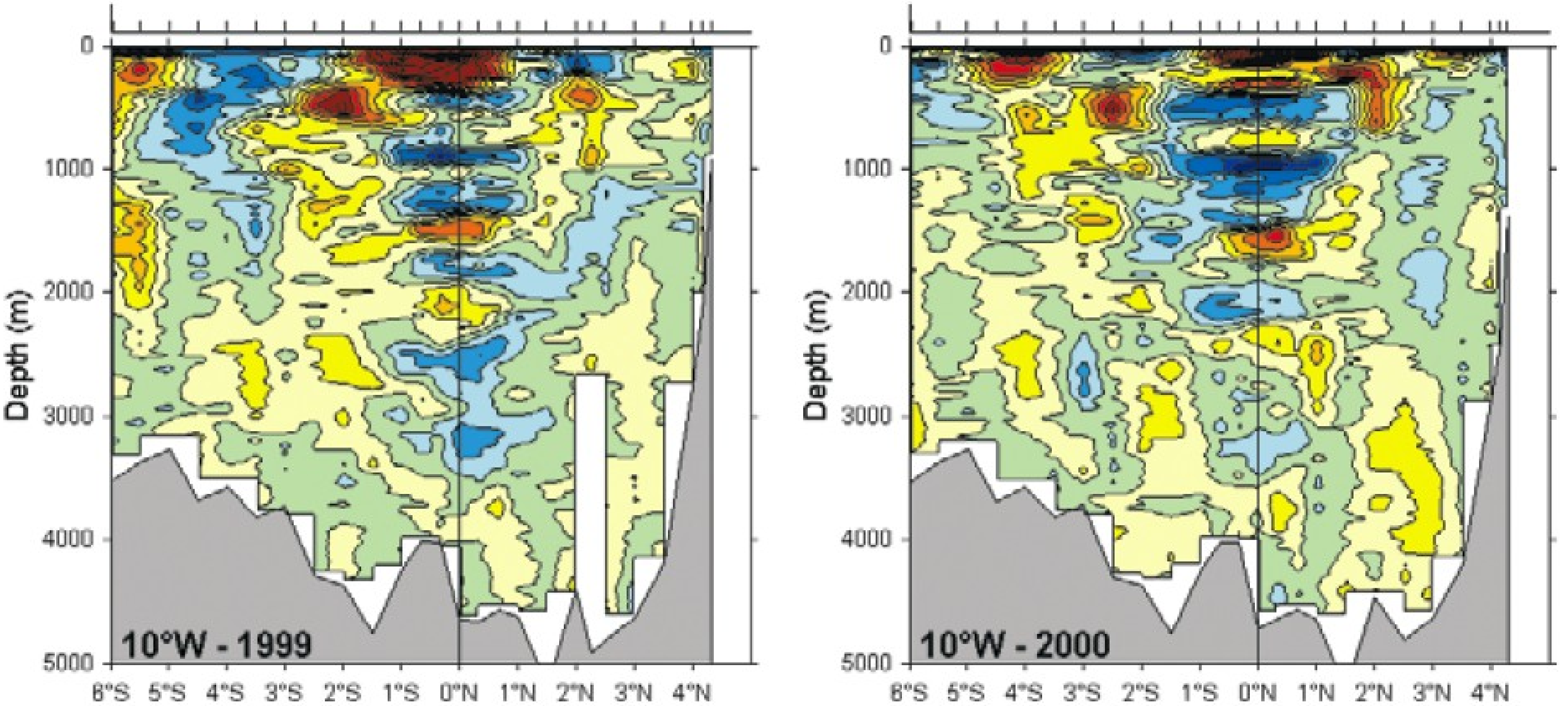
Equatorial Deep Jets in the Atlantic

- Strong EDJ in meridional ship sections along 10°W
- Weakening of EDJ from 10°W toward 0° and 6°E



Bourlès et al. 2003

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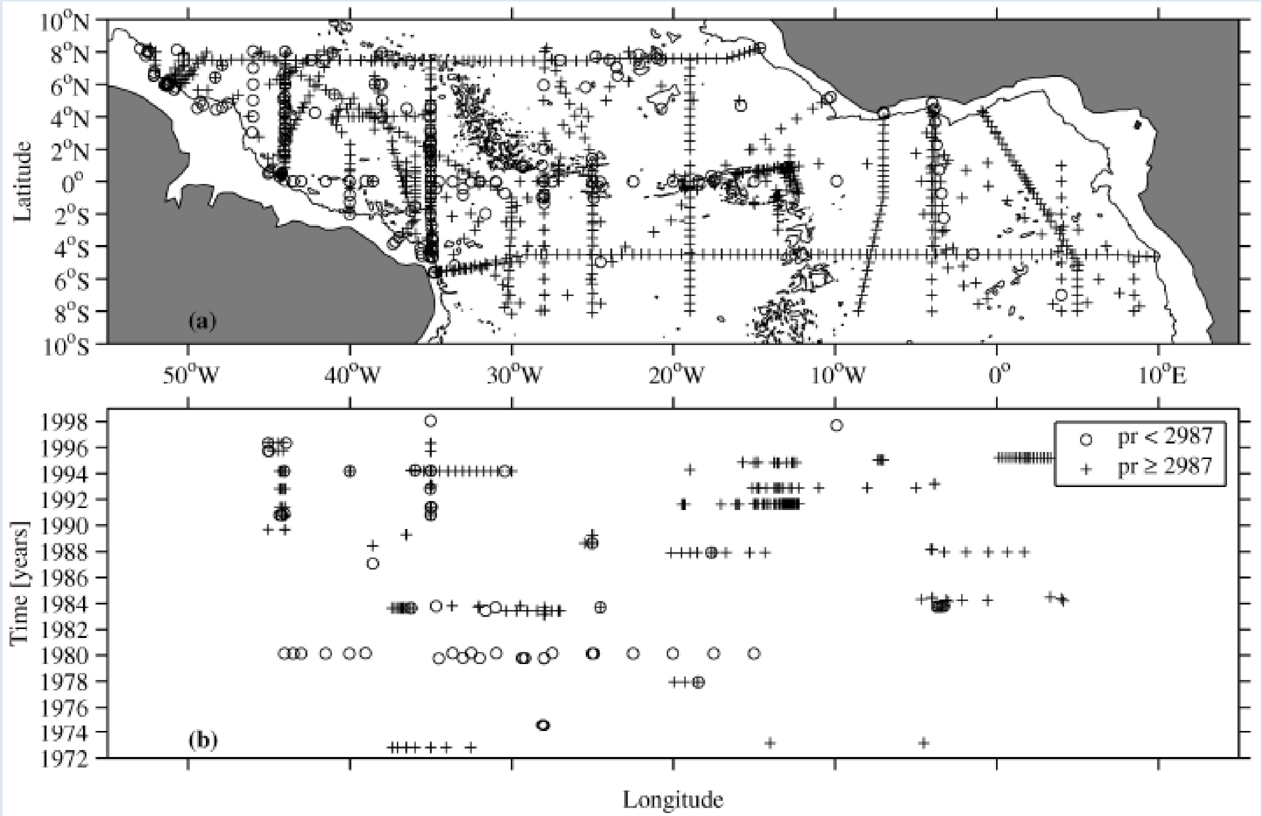
Equatorial Deep Jets in the Atlantic

- Analysis of vertical strain from deep CTD data within ±2.75° off the equator.
- 5±1 years period
- 660 sdbar vertical wavelength (ref. ~1700dbar)
- 70°±60° zonal wavelength
- Downward and westward phase propagation



Johnson & Zhang 2003

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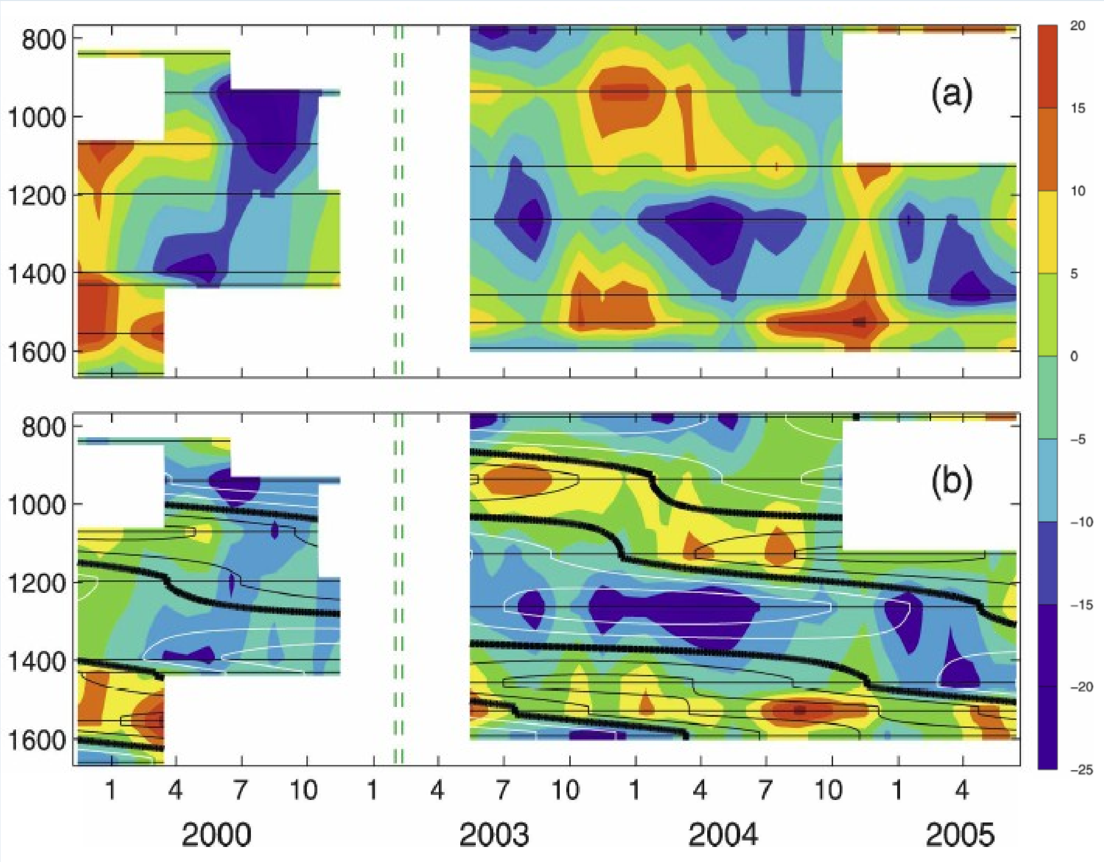
Equatorial Deep Jets in Current Meter Moorings (10°W)

- Analysis of zonal velocity from current meter moorings at 10°W
- Plane wave fit (contours) to data yield
  - Period of 4.4 years
  - Vertical wavelength (ref. ~1000m) of 440 sm
  - Downward phase propagation



Bunge et al. 2008

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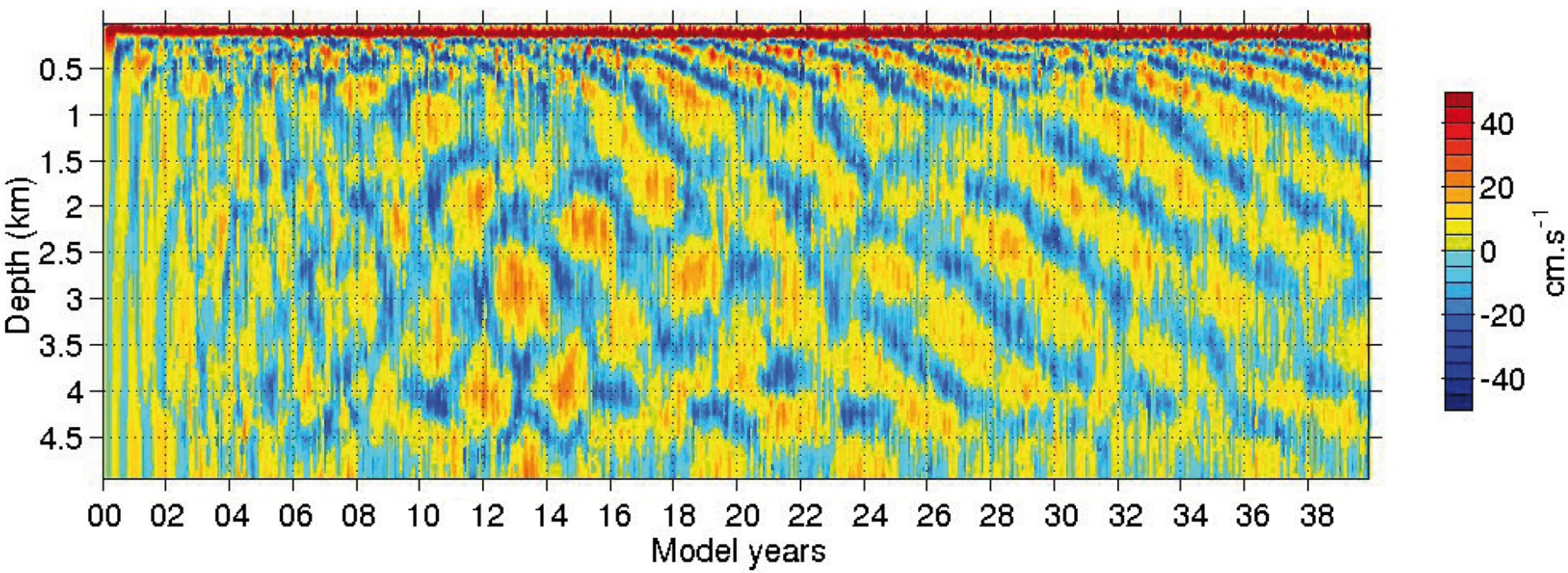
Equatorial Deep Jets

- How are the Jets forced?
  1. Inertial Instability (Hua et al. 1997, d'Orgeville et al. 2004, Eden and Dengler 2008)
  2. Destabilization of Rossby-gravity waves (d'Orgeville et al. 2007, Hua et al. 2008, Ménesguen et al. 2009)
- d'Orgeville et al. (2007) suggested that EDJ can be described by equatorial basin modes (Cane & Moore 1981) setting their time scale.
- Upward energy propagation toward the surface hindered by the EUC (e.g. McPhaden et al. 1986) or tunneling through the shear zone (Brown & Sutherland 2007)?

Idealized Simulations of EDJs

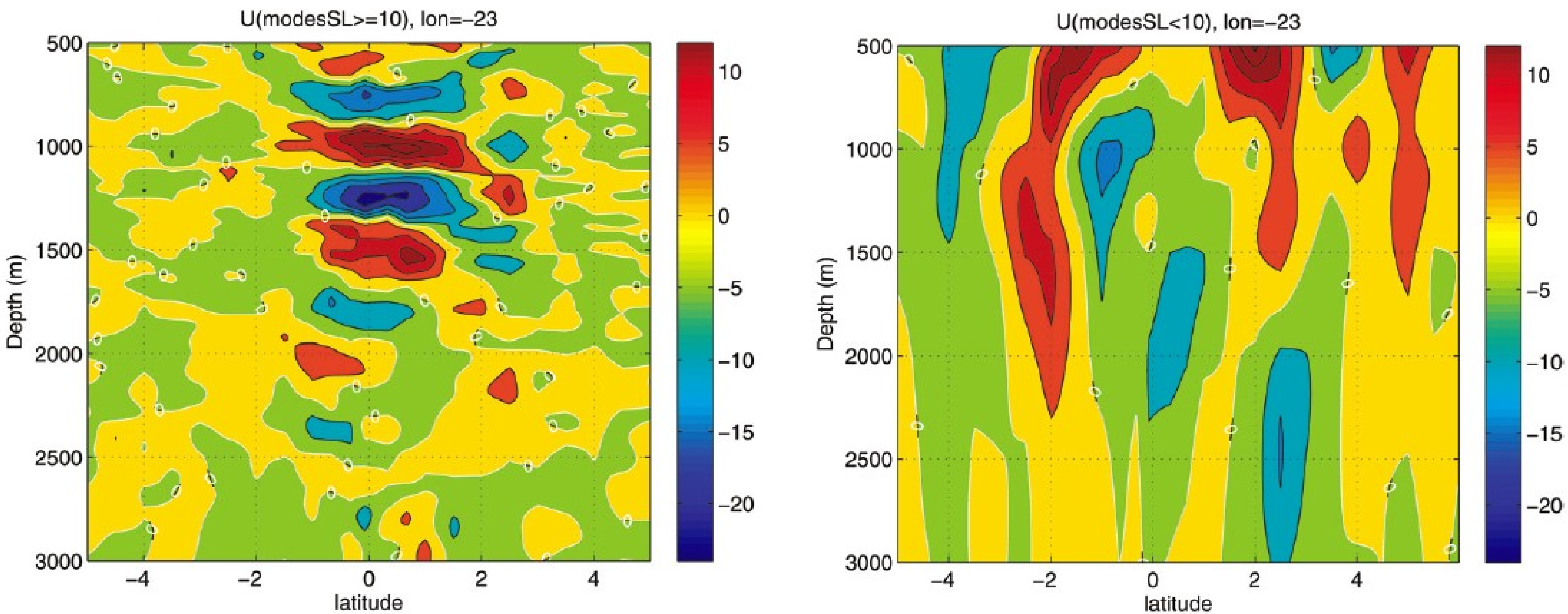
- EDJ generated in an idealized model (1/4°, 100 levels, low horizontal and vertical mixing) forced with constant wind
- Tropical instability waves provide energy for EDJ generation
- Establishment of dissipative high-baroclinic basin modes



Ascani, Wang, Firing, McCreary (AGU meeting, 2006)

Idealized Simulations of EDJs

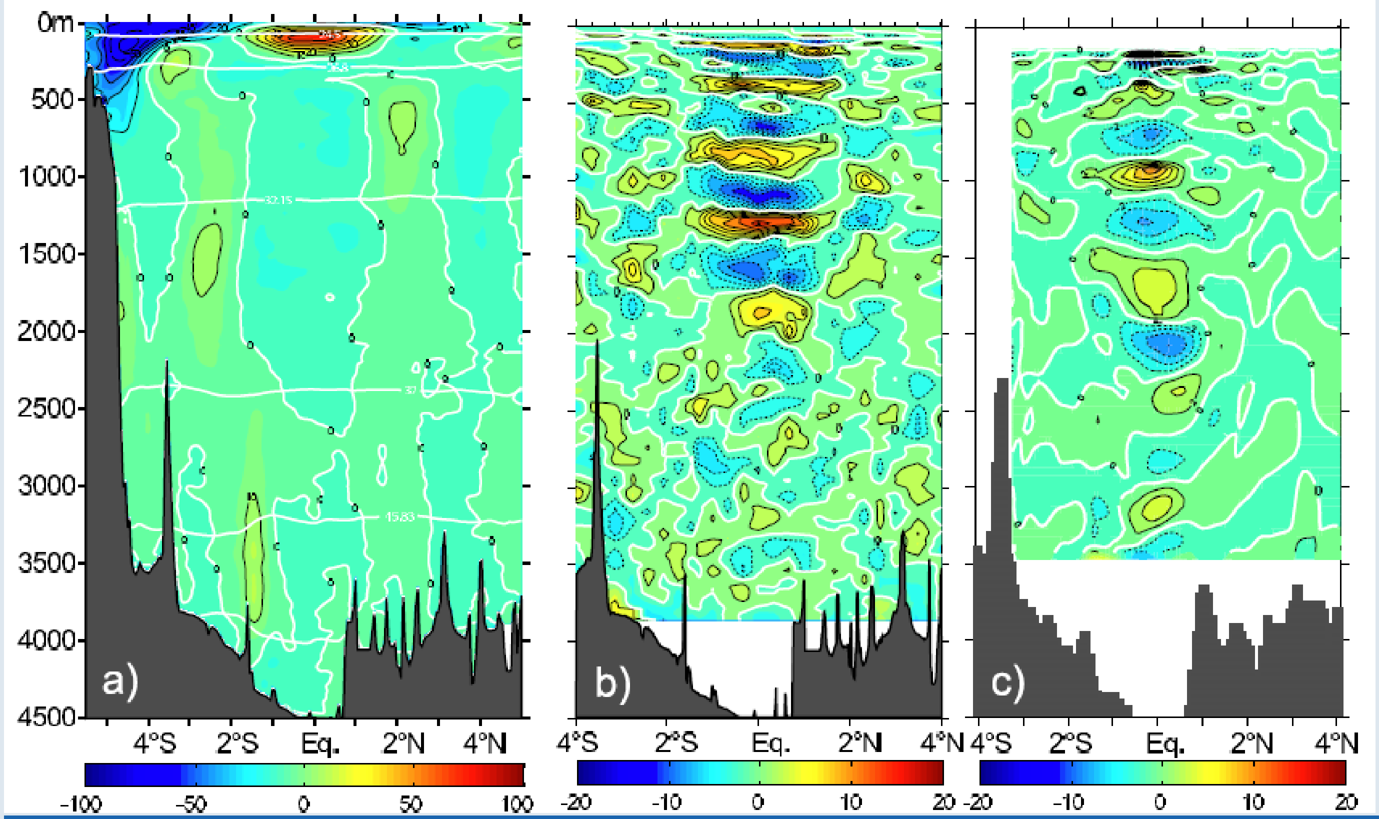
- Idealized model (1/4°, 100 levels) forced by oscillations at the western boundary producing Rossby-gravity waves
- Both, EDJ and extra-equatorial jets (EEJ) are generated in this simulation



Ménesguen et al. 2009

Realistic OGCM Simulation

- EDJ are found to be related to the DWBC; inertial instability may be important for their generation
- EDJ strength increase with increasing vertical and horizontal resolution, but are still underestimated

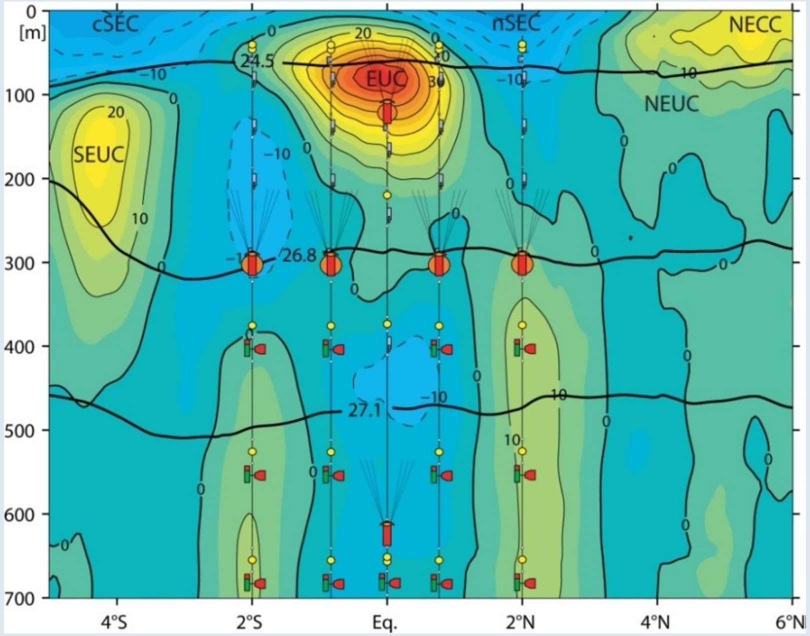


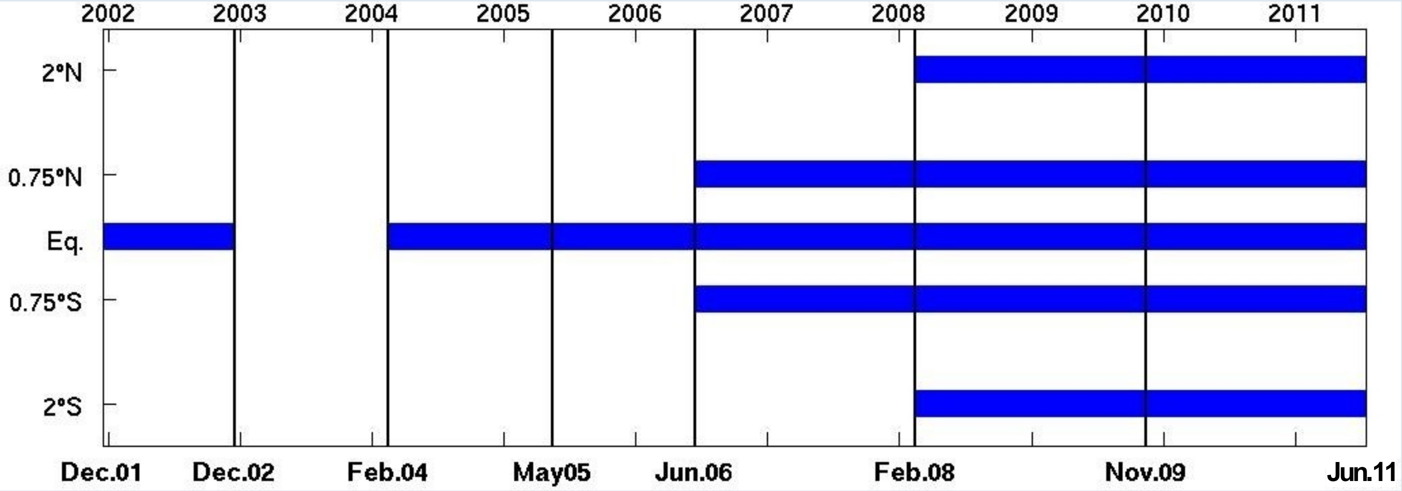
Observed mean flow (a) and observed (b) and simulated (c) EDJ; 1/12°, 94 levels

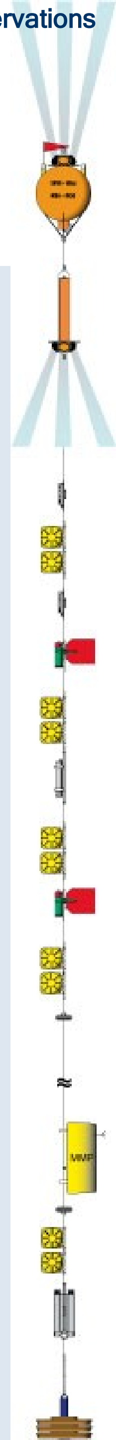
Eden and Dengler (2008)

Interannual Current Variability at the Equator, 23°W

- Current meter mooring array in the frame of BMBF Nordatlantik.
- Cooperation with PIRATA (Bernard Bourlès) provide shallow ADCP
- From Jun 06 - Feb 08 deep ocean moored profiler provided by John Toole (WHOI)







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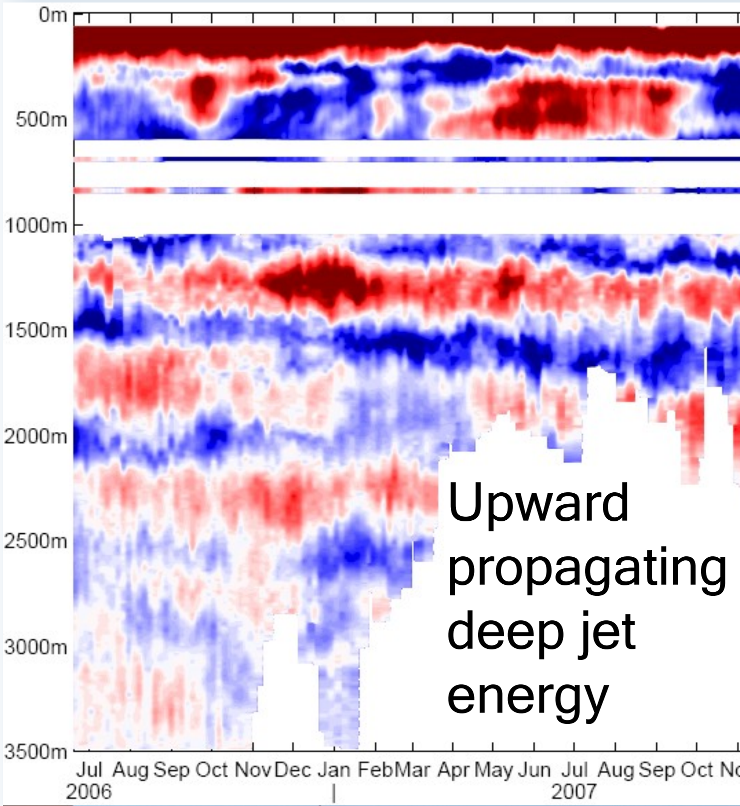
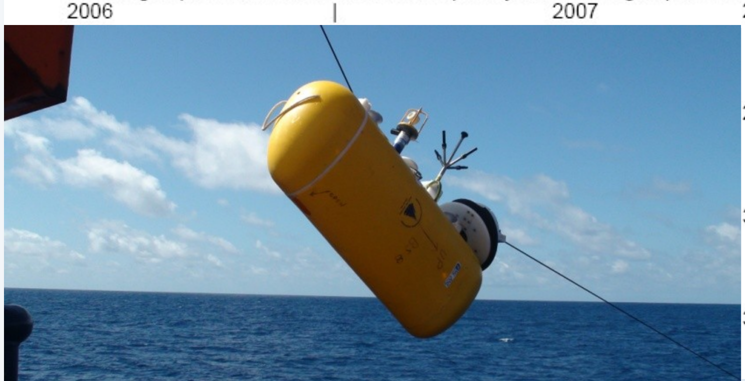
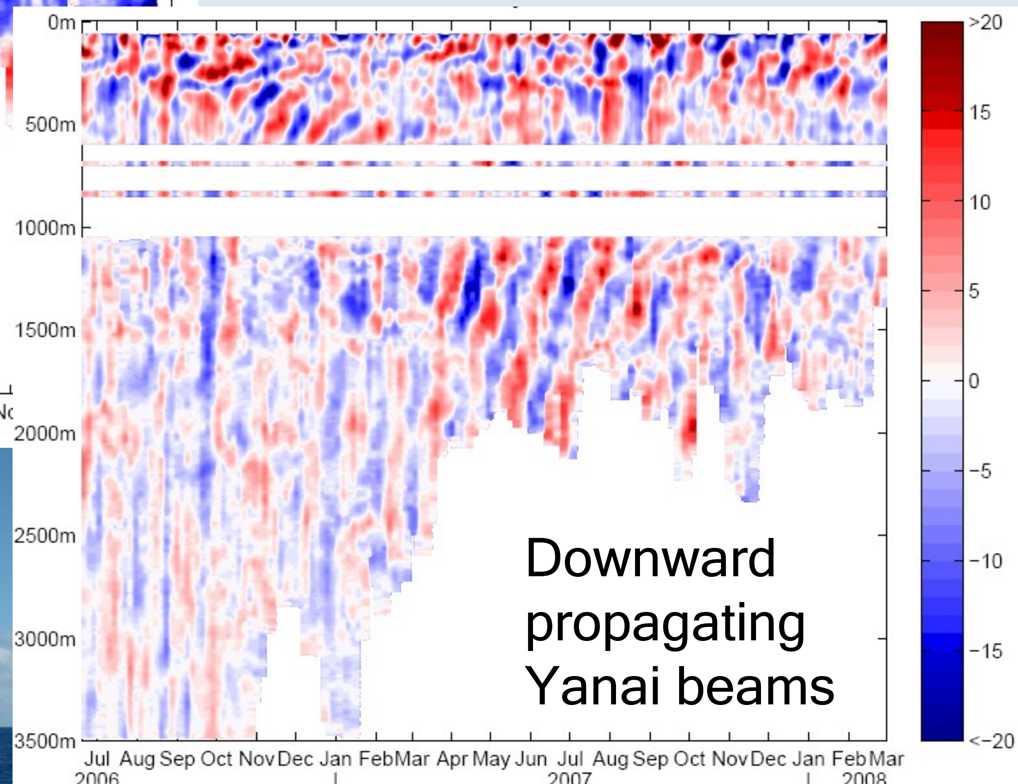
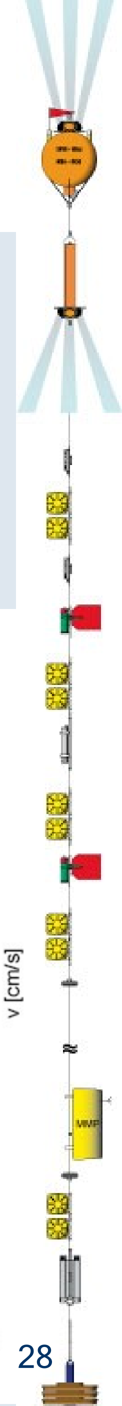
Equatorial Dynamics

Zonal (left) and meridional (right) velocity [m/s] measured at 23°W, 0°N with ADCP and moored profiler



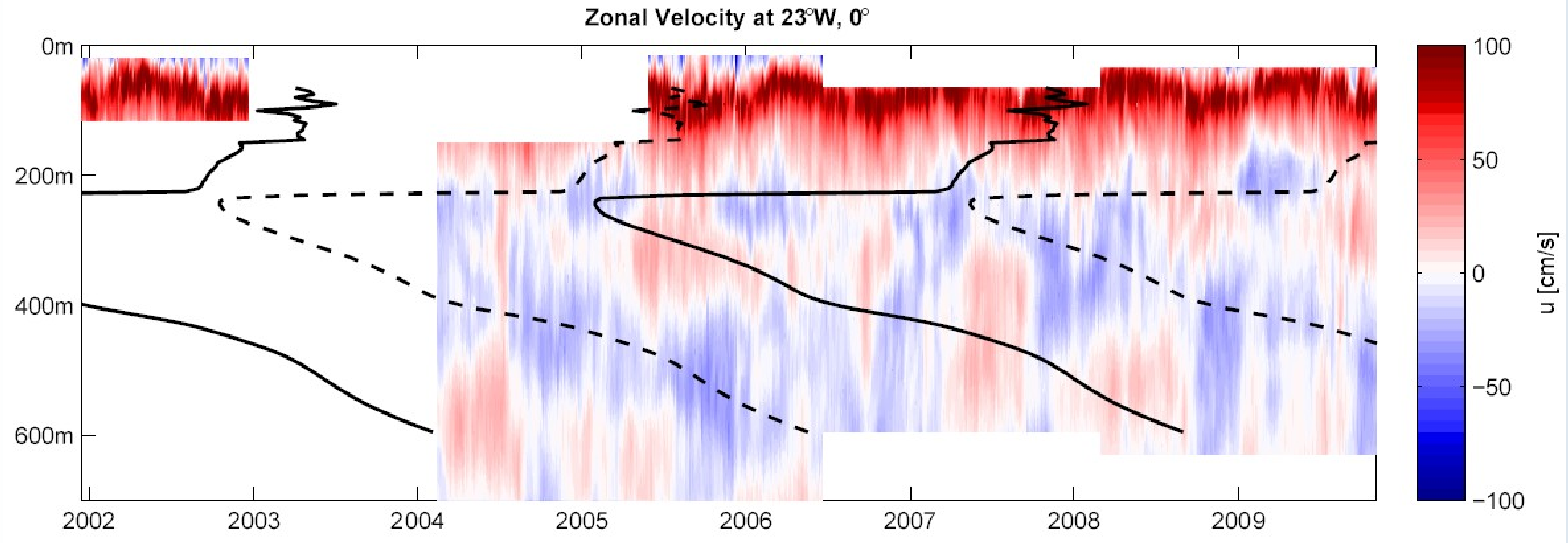




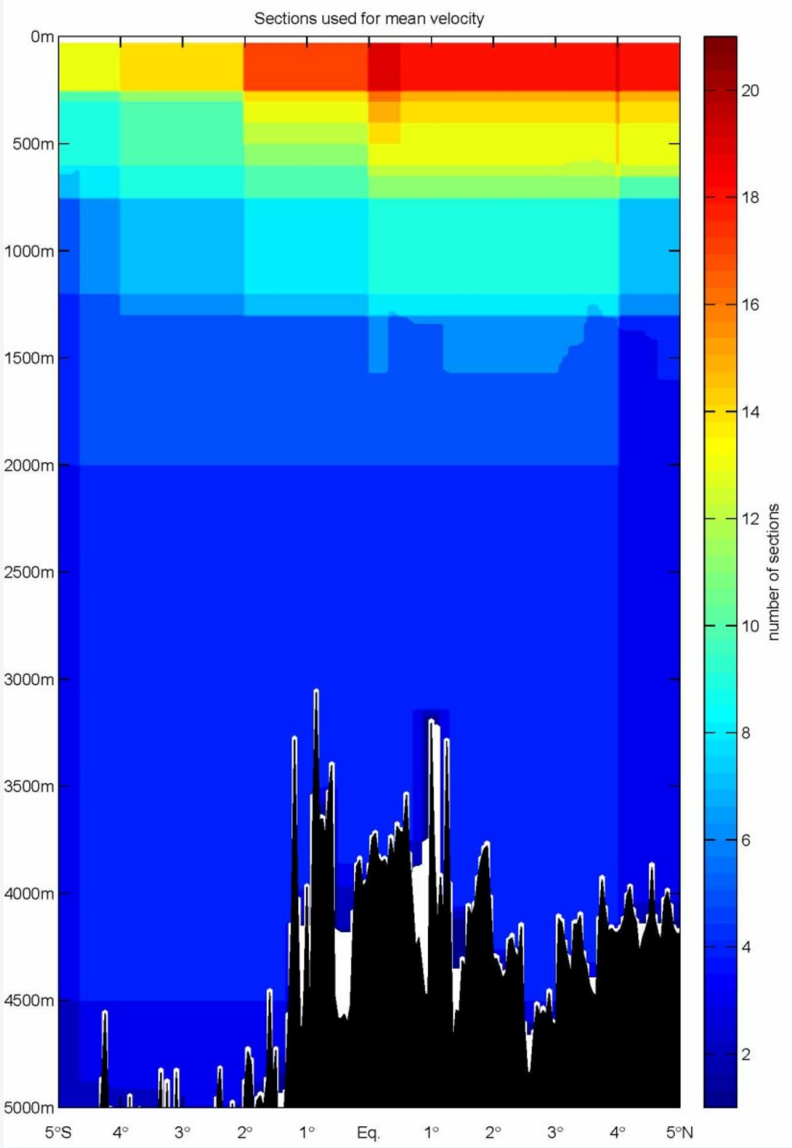


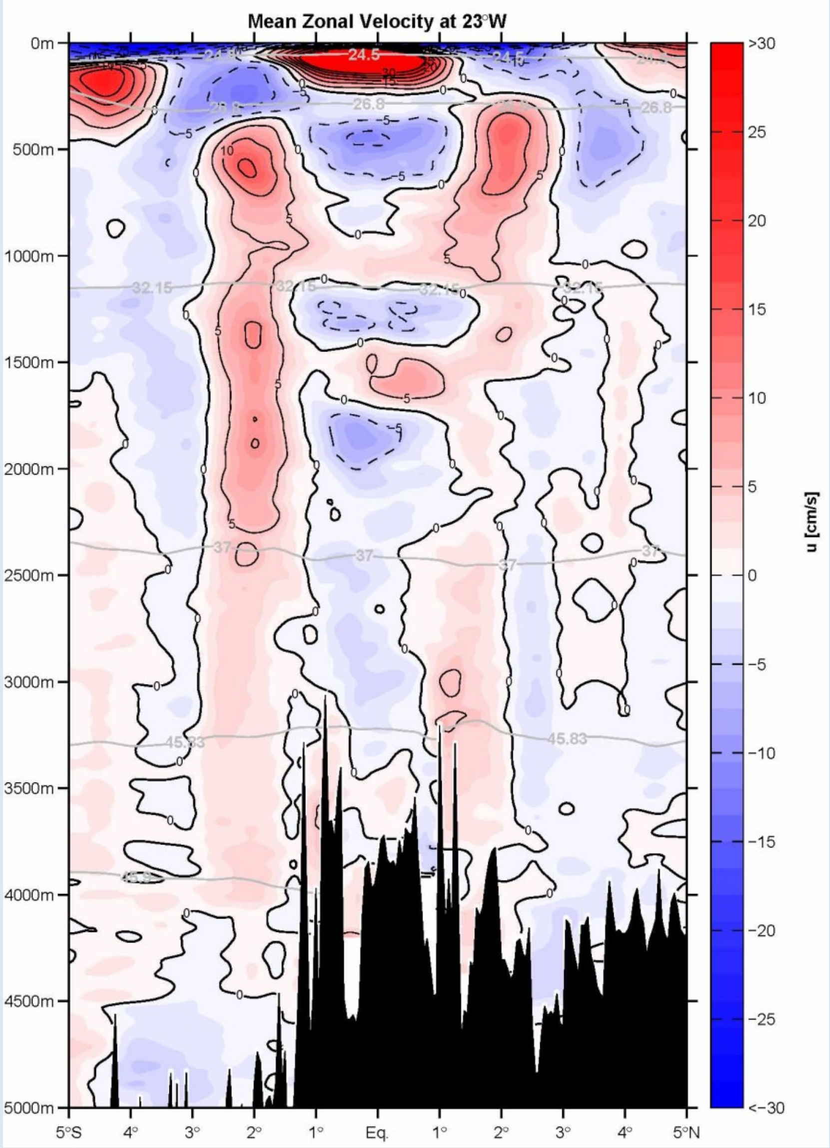
Equatorial Deep Jets (EDJ) in the Upper Ocean

- Consistent downward phase propagation below the EUC
- 4.5-year cycle also within the EUC
- Phase jump at about the critical level (Kelvin wave speed equals the background flow speed)



Mean Zonal Velocity, 23°W





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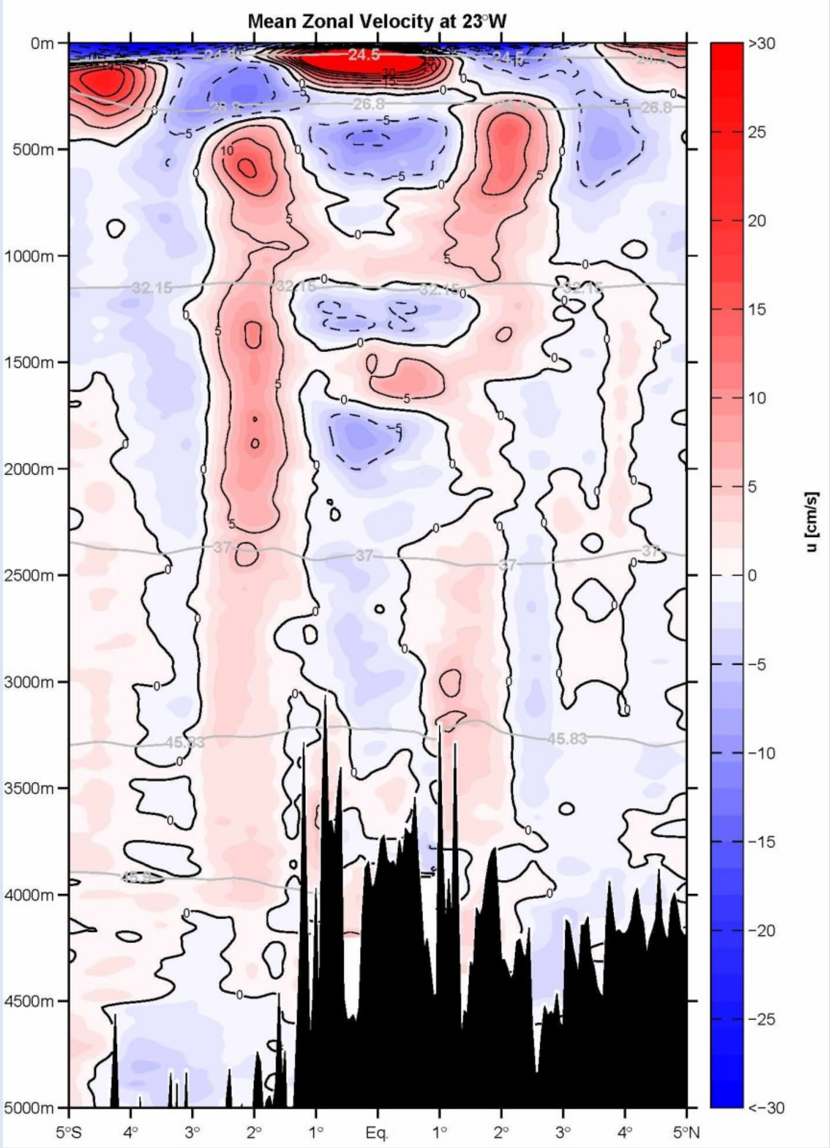
Mean Zonal Velocity, 23°W

- Equatorial tall jets (SICC/NICC) at 2°S/2°N
- Stronger flow in southern hemisphere
- Intermediate and deep equatorial flow dominantly westward
- Remnants of EDJs present (or quasi-stationary jets, Bunge et al., 2008?)



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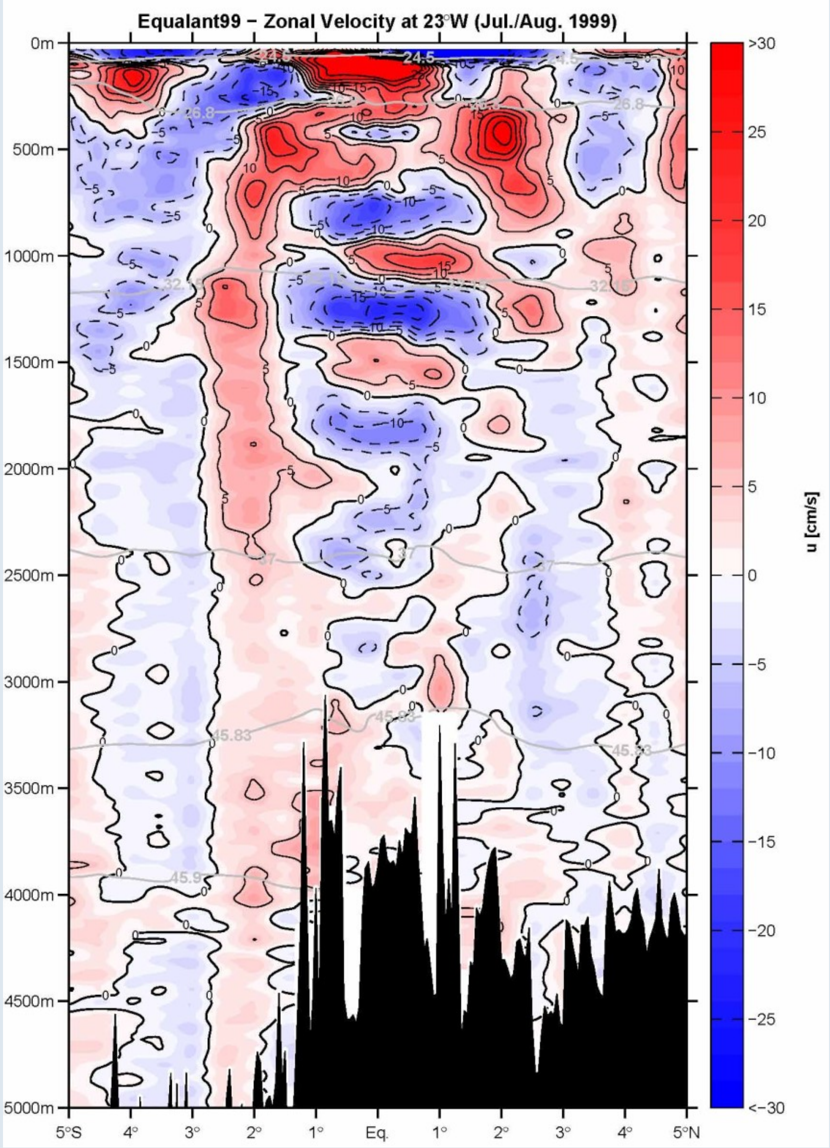
Zonal Velocity – Jul/Aug 1999

- Single sections with EDJ amplitudes of more than 15 cm/s
- Maximum EDJ amplitudes at about 1000 to 1500m depth



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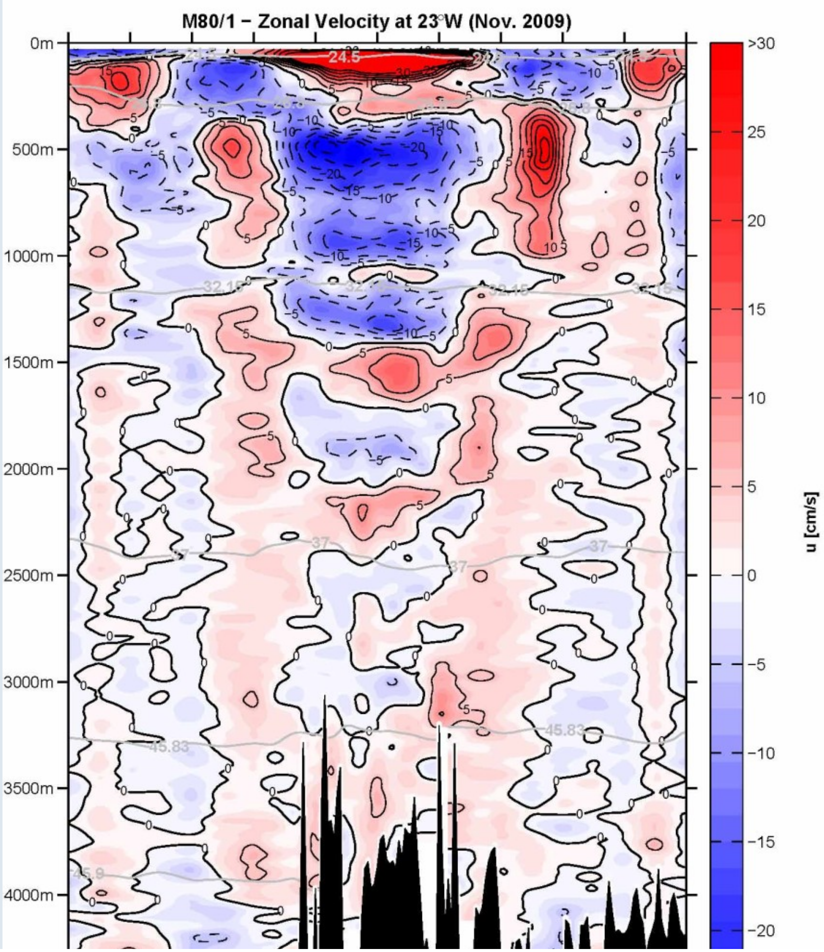
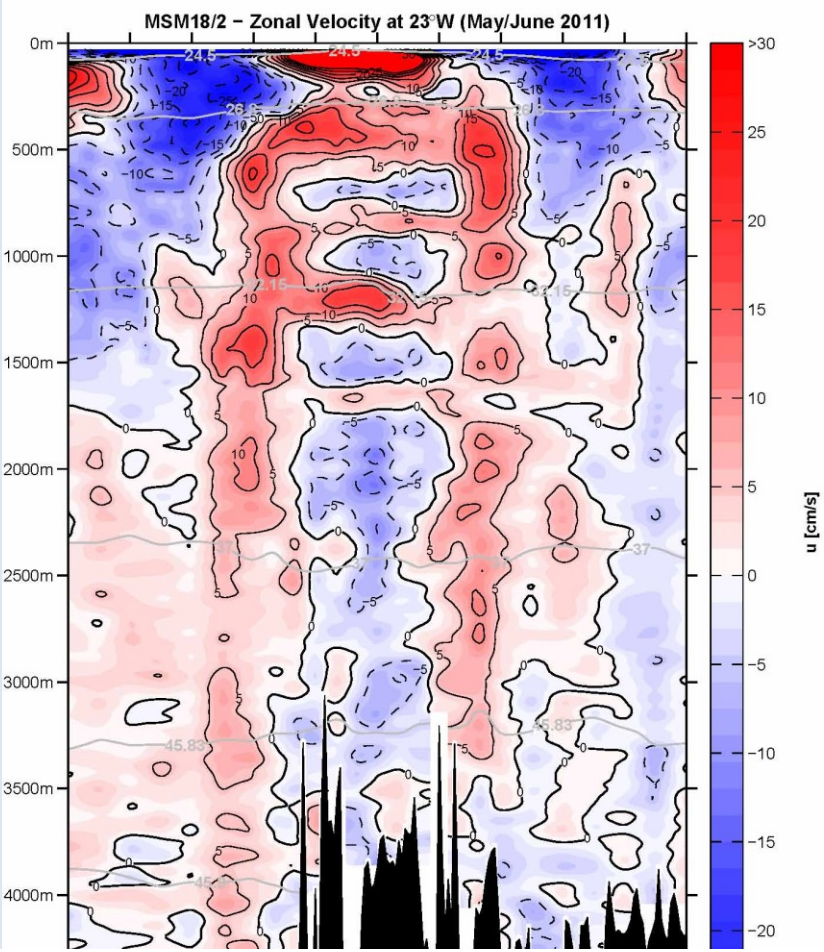
Nov 2009 - May/Jun 2011

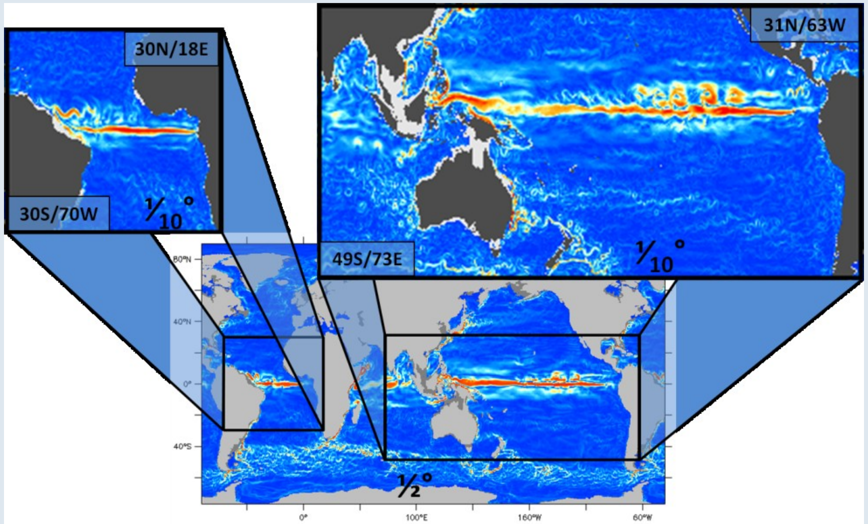


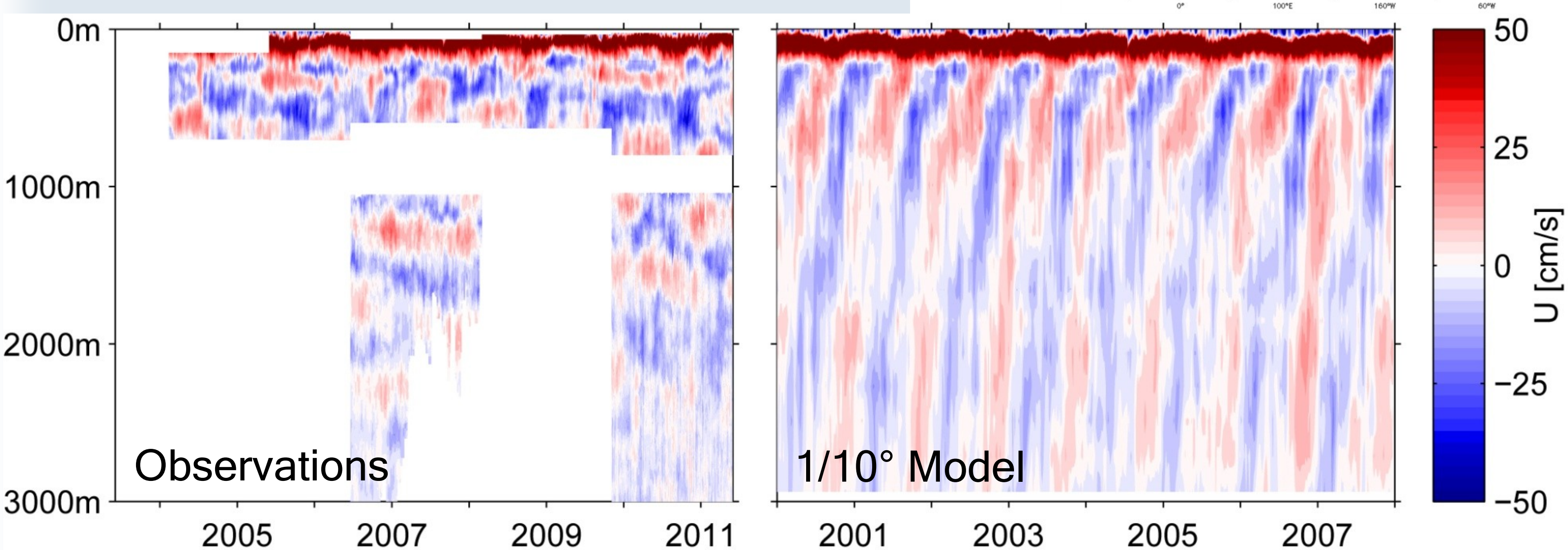


- Superimposed low-baroclinic-mode variability associated with seasonal cycle

Observations versus Model

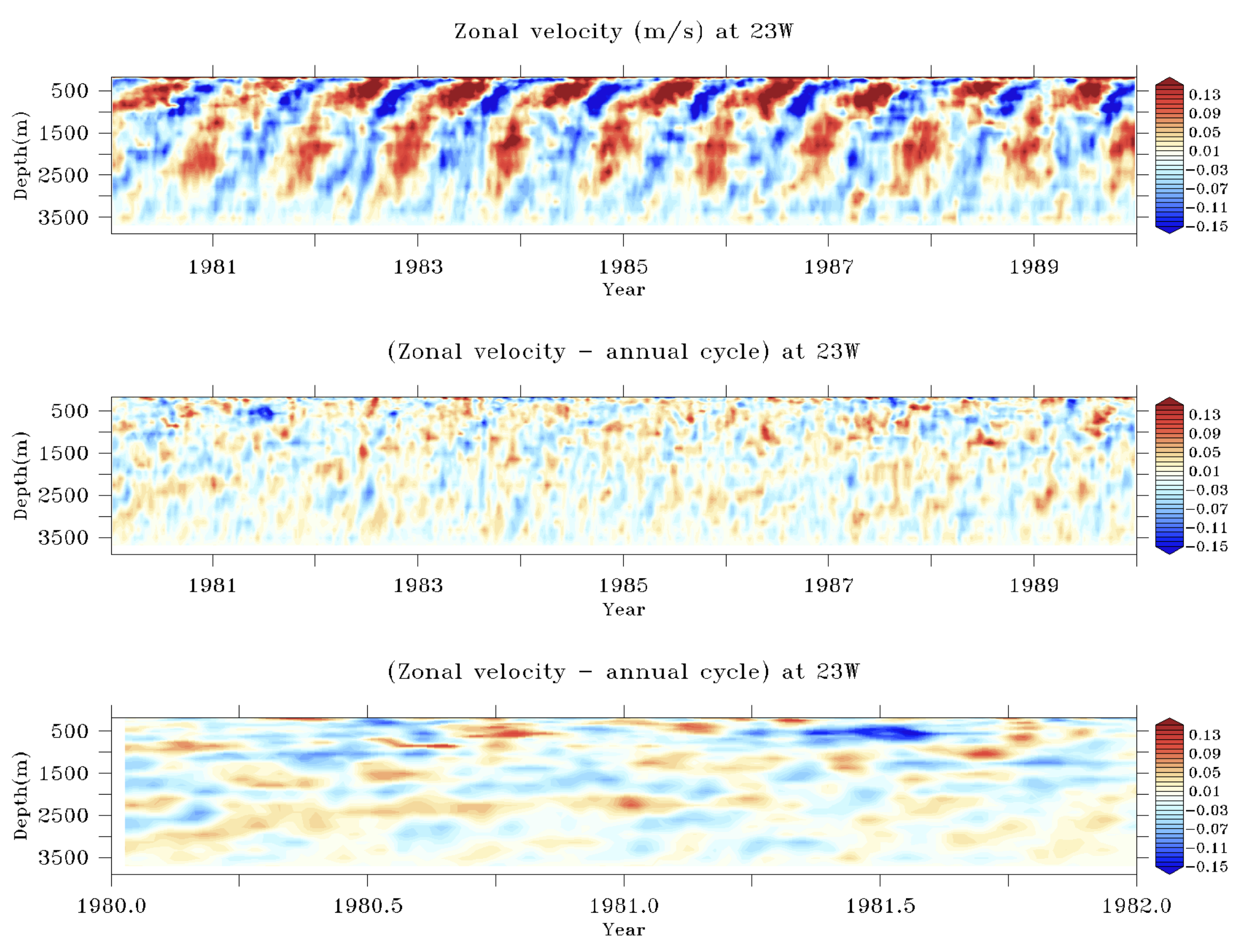
- State-of-the-art, high-resolution model (ORCA, 45 vertical levels) does not represent EDJ (pers. comm. C. Böning)
- Simulation is dominated by low-baroclinic mode variability





Higher Vertical Resolution

- Higher vertical resolution (75 vertical levels) still does not permit EDJs (pers. comm. Andrew C. Coward, SOC)



Summary (1)

- 4.5-year cycle detected in SST and surface flow associated with distinct wind and rainfall pattern
  - Small meridonal scales of surface flow
  - No seasonal dependence of surface flow variability
- EDJ basin mode suggested as source of this cycle
  - Upward energy propagation
- Oscillations can be exploited to improve predictions of tropical Atlantic SST
- Need of ocean simulations with high horizontal and vertical resolution and low dissipation

Variability in the Global Equatorial Ocean (1000m) from Argo

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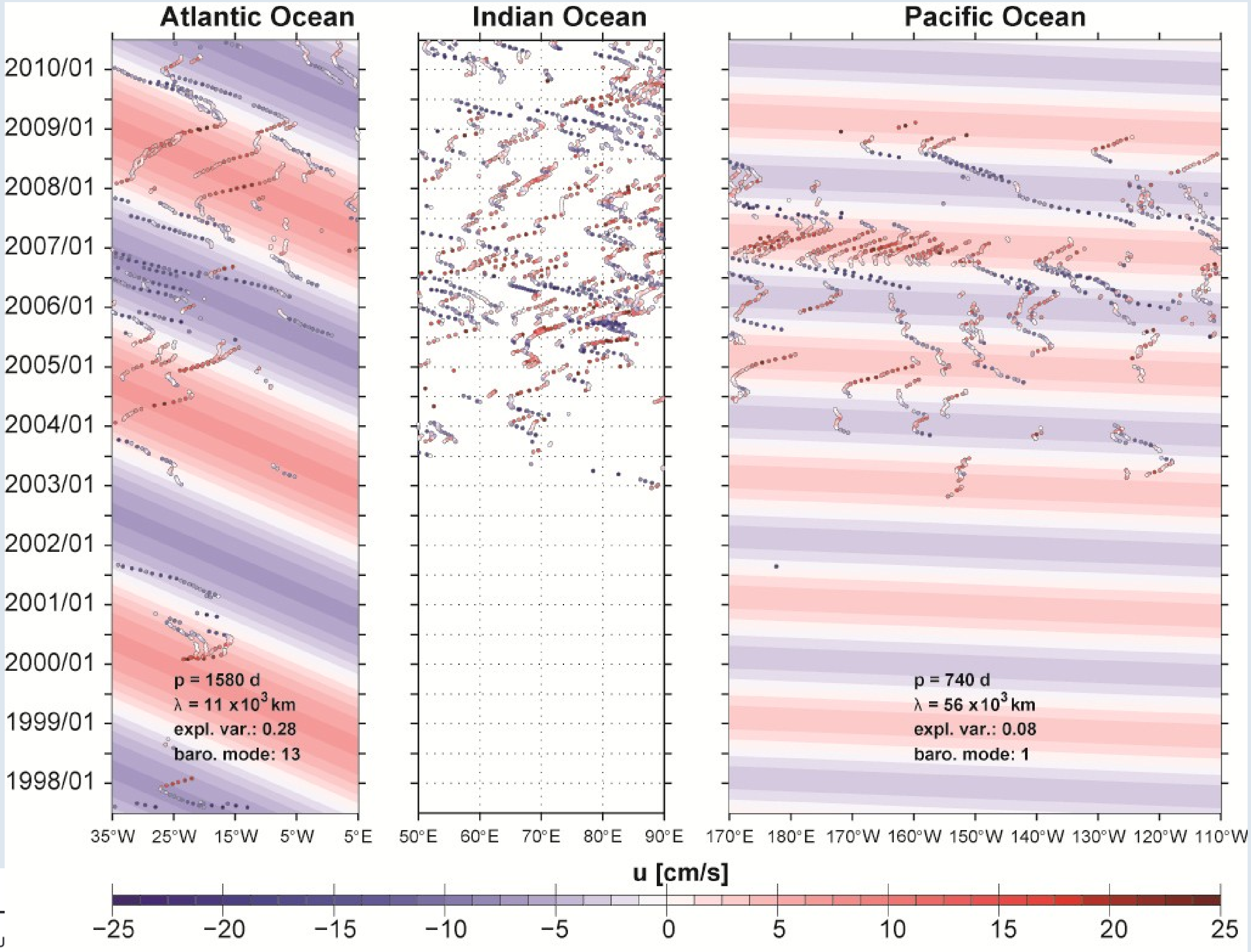

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Summary (2)

- Argo data show that 4.5-year Atlantic cycle associated with slowly propagating high-baroclinic mode waves is the dominant variability at depth
- Besides similar geometry, there are mostly incoherent signals at 1000m in the Indian Ocean
- Pacific variability is dominated by fast propagating (probably wind generated) waves
  - EDJ period about 30 yr (Johnson et al. 2002)

We expect no influence of Equatorial Deep Jets on Indian and Pacific SST on interannual time scales.

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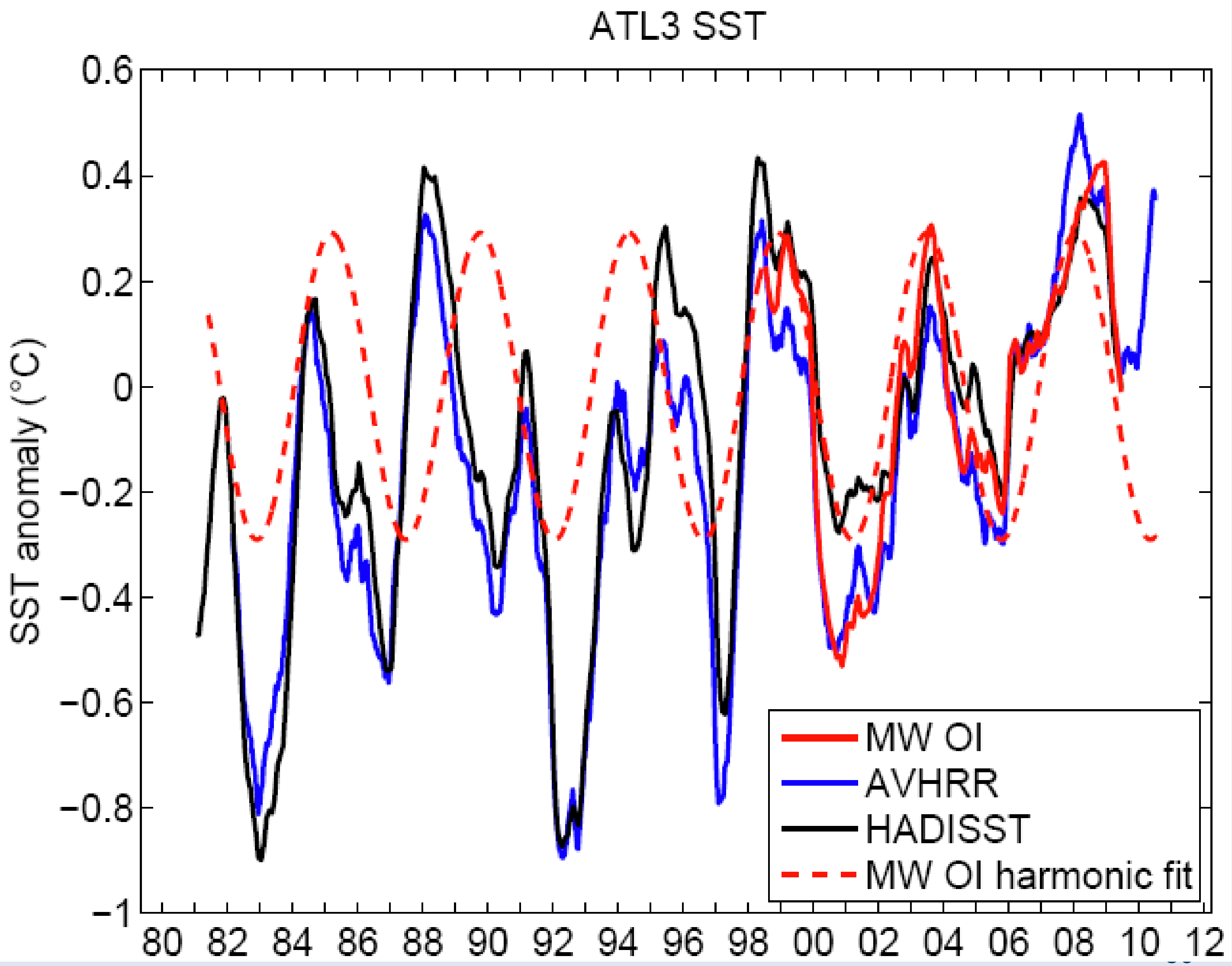
Longer SST time series

- More irregular behavior on longer time scales.



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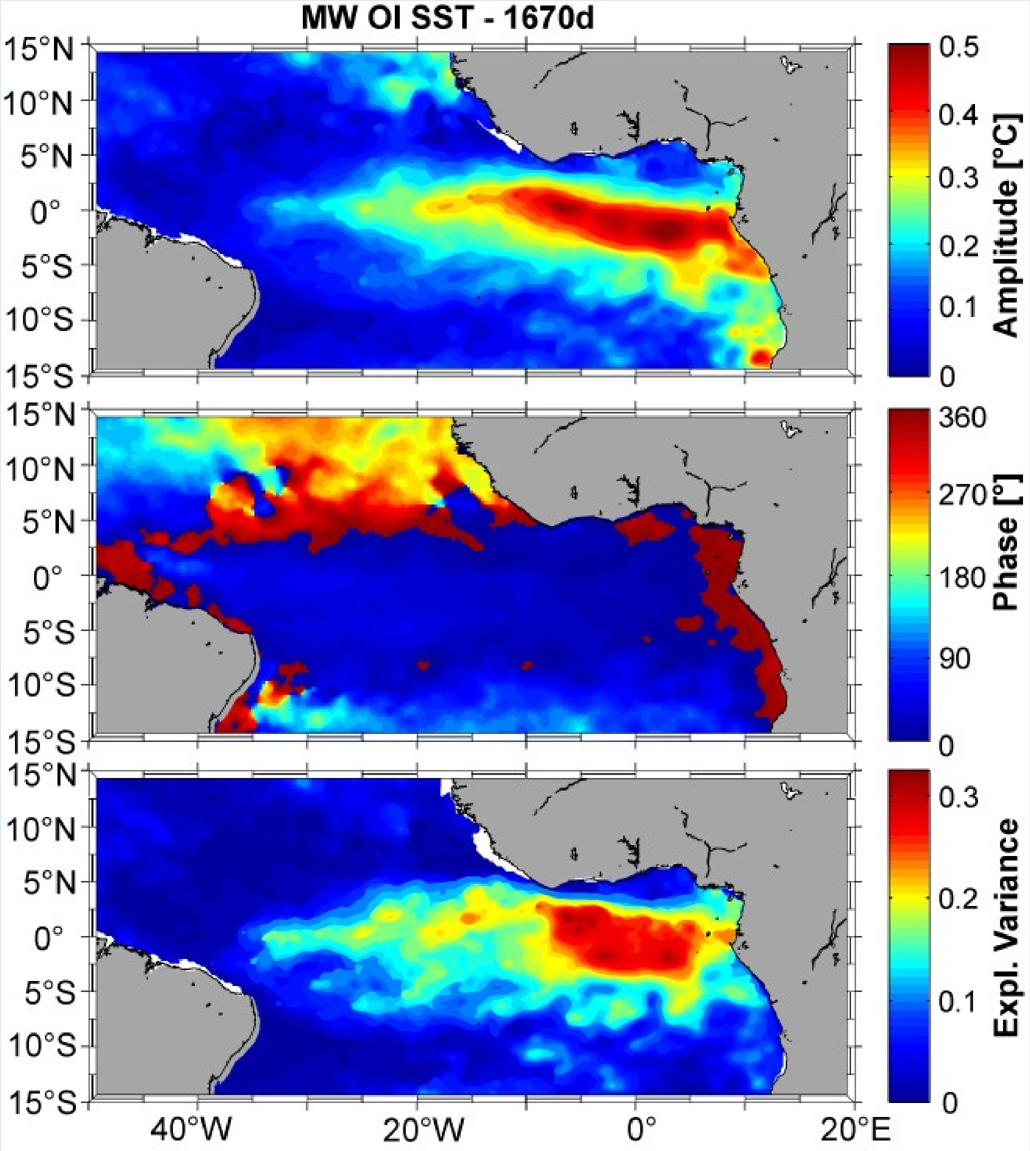
Pattern of the 4.5-year Cycle in Microwave OI SST

- Amplitude, phase, and explained variance of the 1670d harmonic of SST (Microwave OI SST from Jan 98 - Dec 2009)
  - 4.5-year signal is closely confined to the equatorial region
  - phase in the equatorial region varies only slightly
  - explains up to 25% of the variance of monthly SST data after subtracting seasonal cycle



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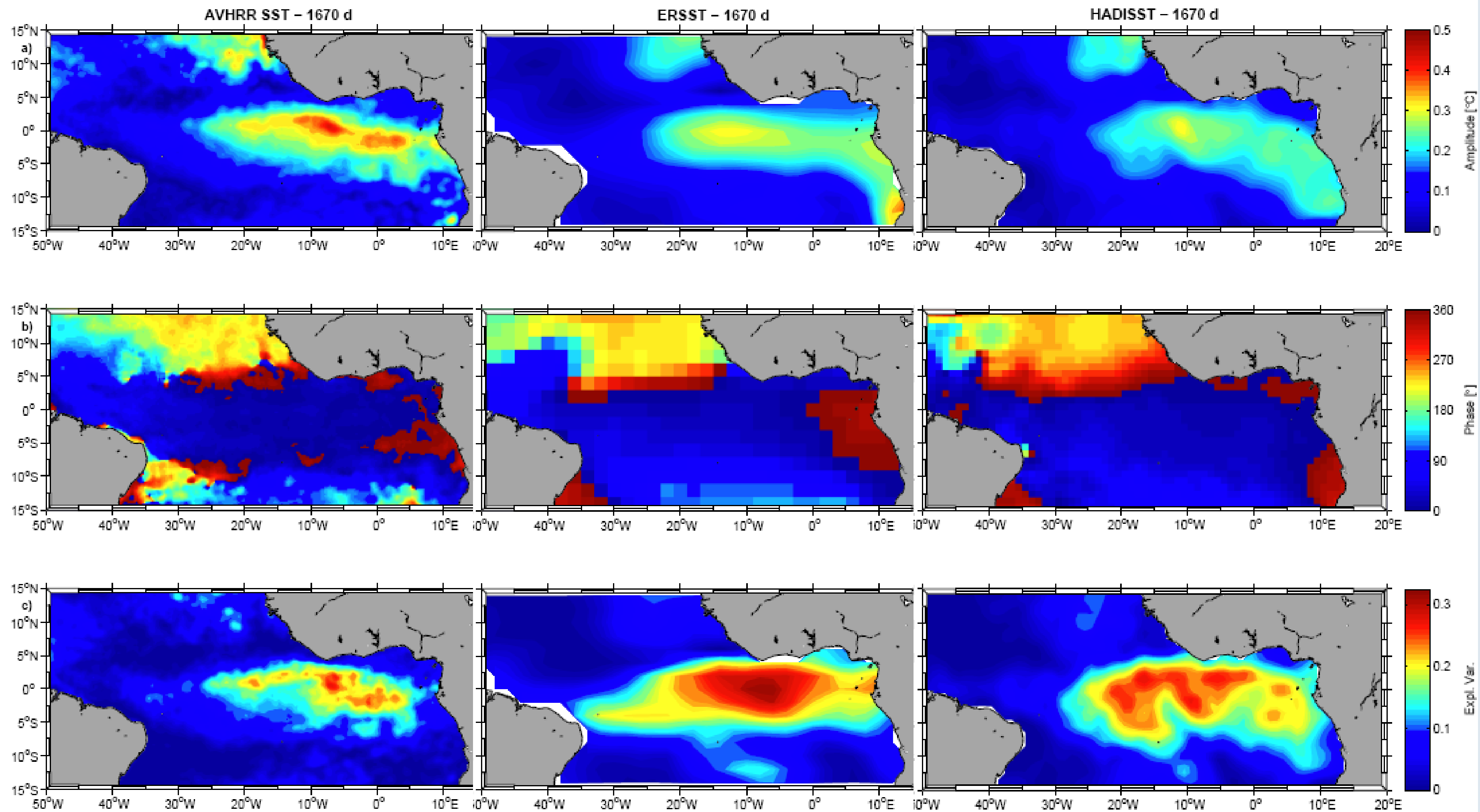
Different SST Data Sets - Same Period of Analysis

AVHRR-only ERSST HADISST



Summary (3)

- Knowledge of the persistence and regularity of EDJ is limited by the availability of high-quality data
  - Influence of other modes of variability
  - Dominant baroclinic mode of EDJ may vary chaotically changing the basin mode period (Ascani pers. comm.)
- Because the SST signal is strongly confined to the equatorial region, high-resolution SST data are required
- 4.5-year cycle is strongly damped in ERSST and HADISST data due to used interpolation schemes